Heavy Elements in Exoplanets:
Planetesimal Accretion vs Pebble Accretion

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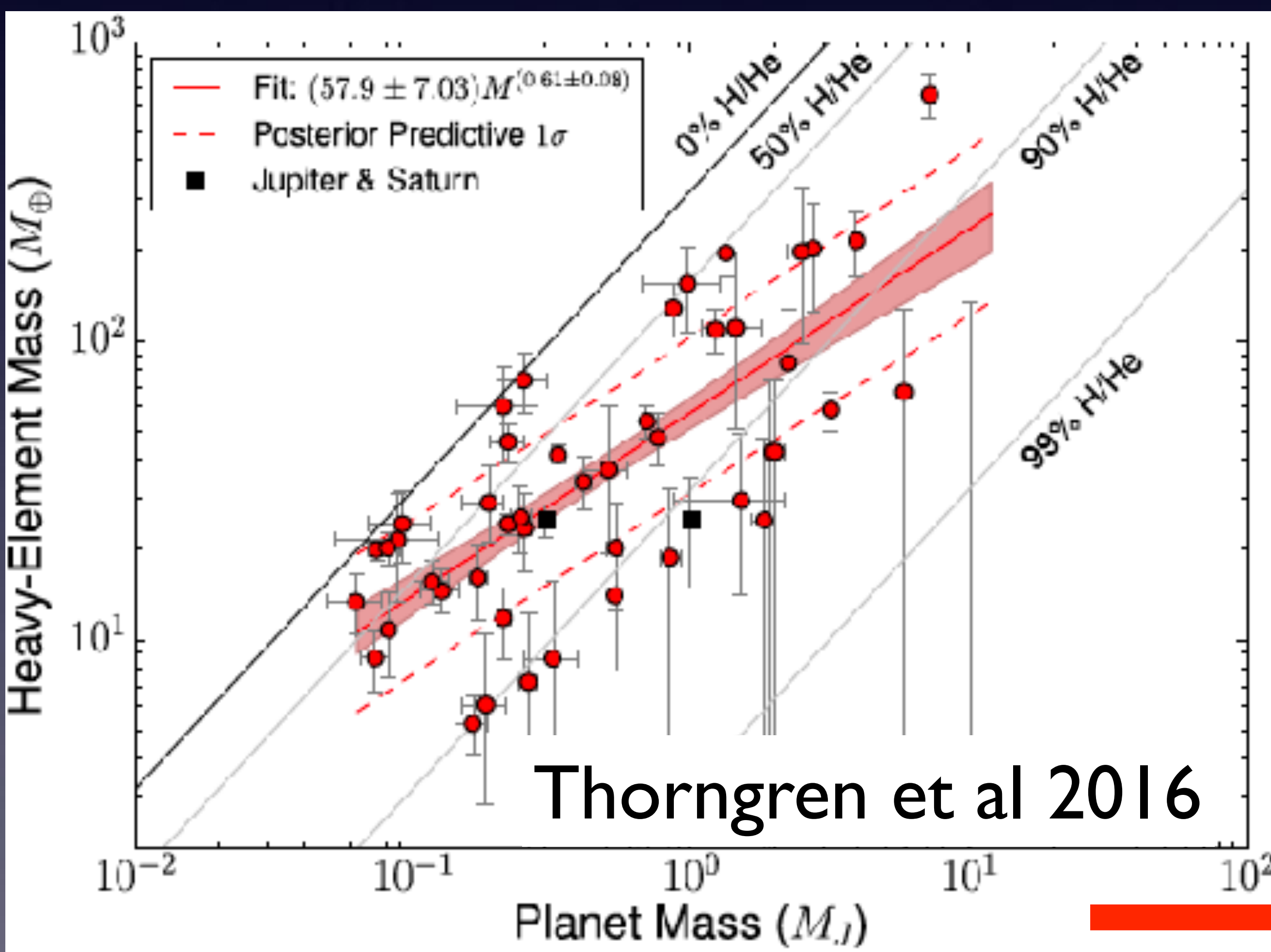
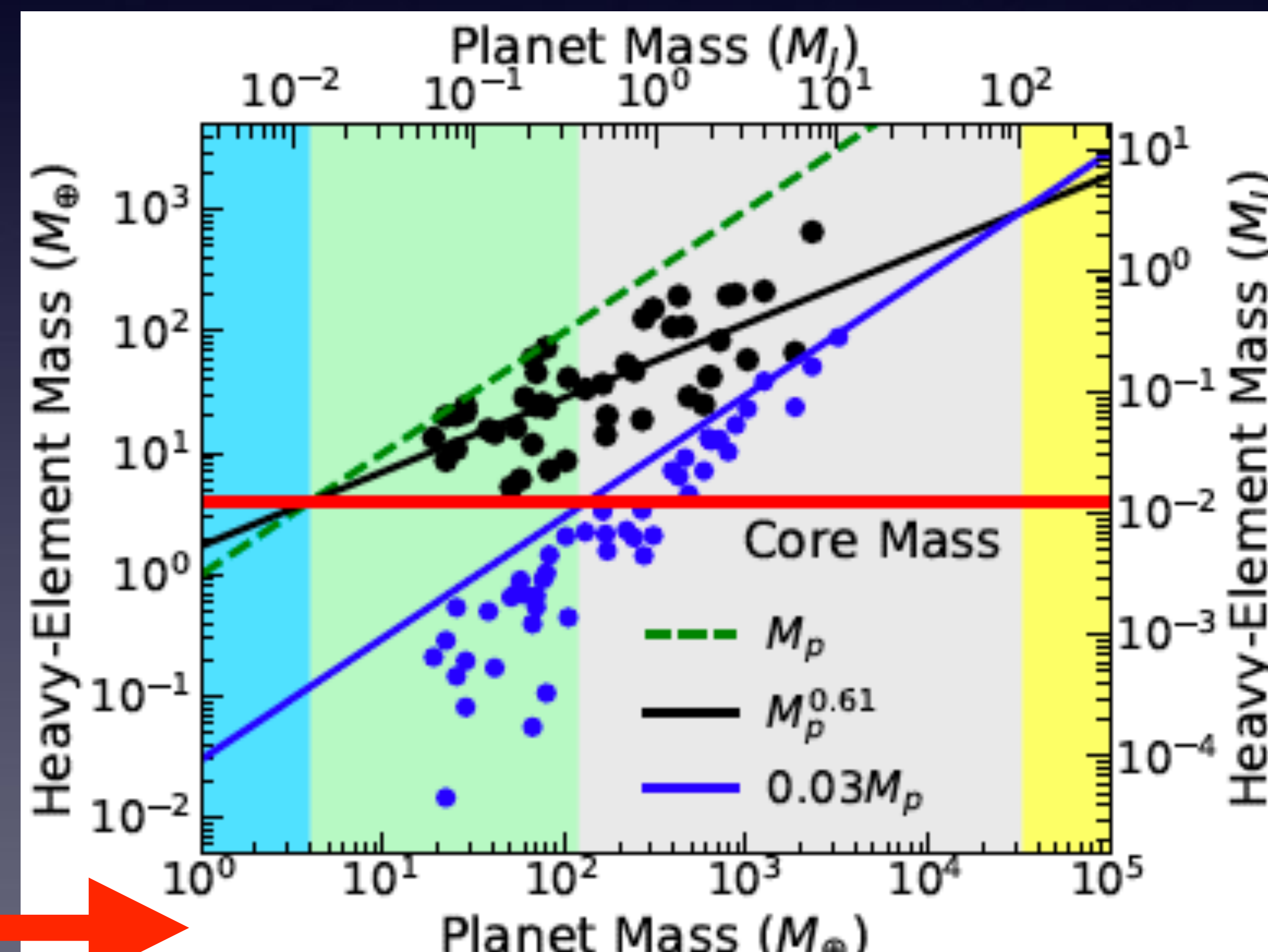
Jet Propulsion Laboratory, California Institute of Technology

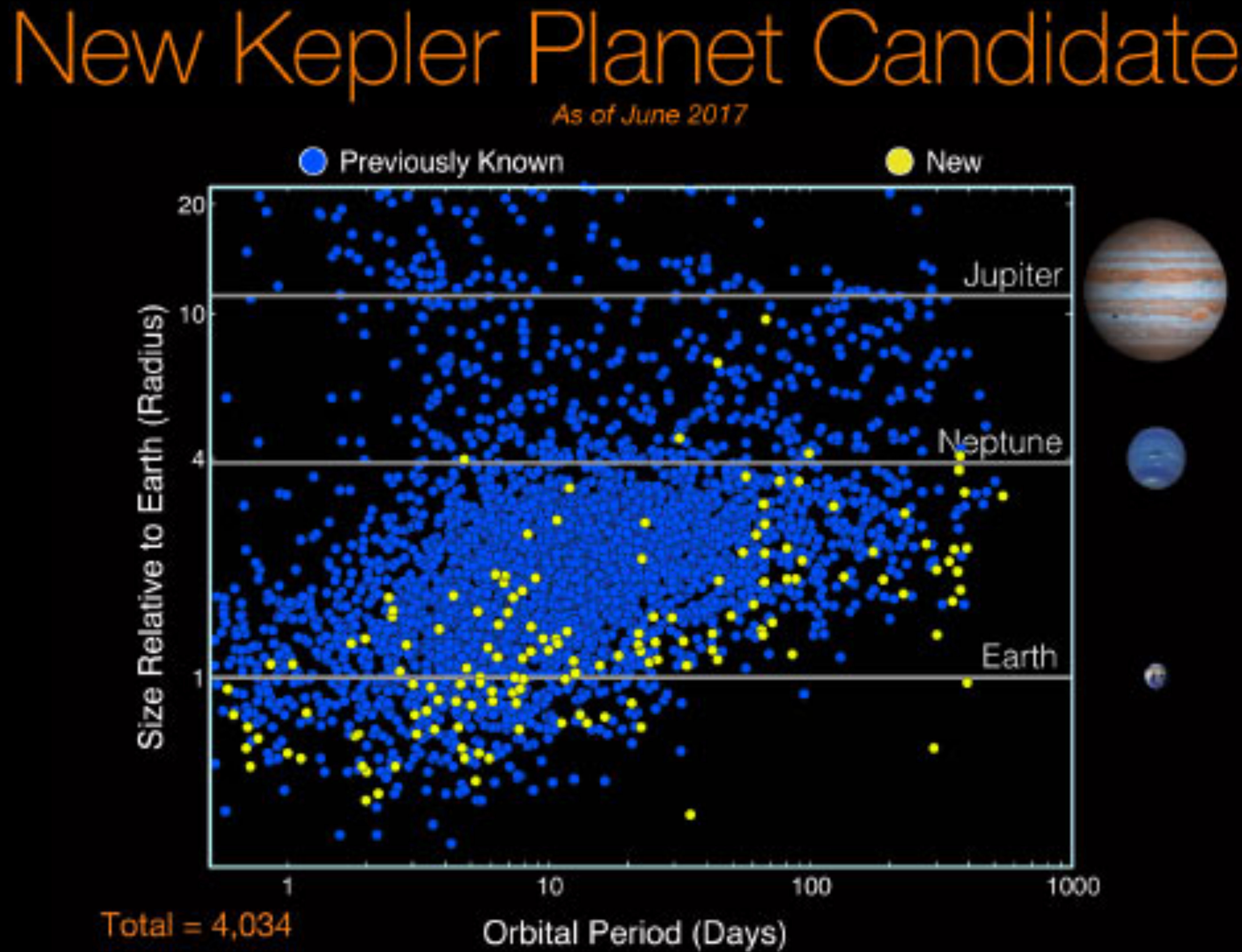




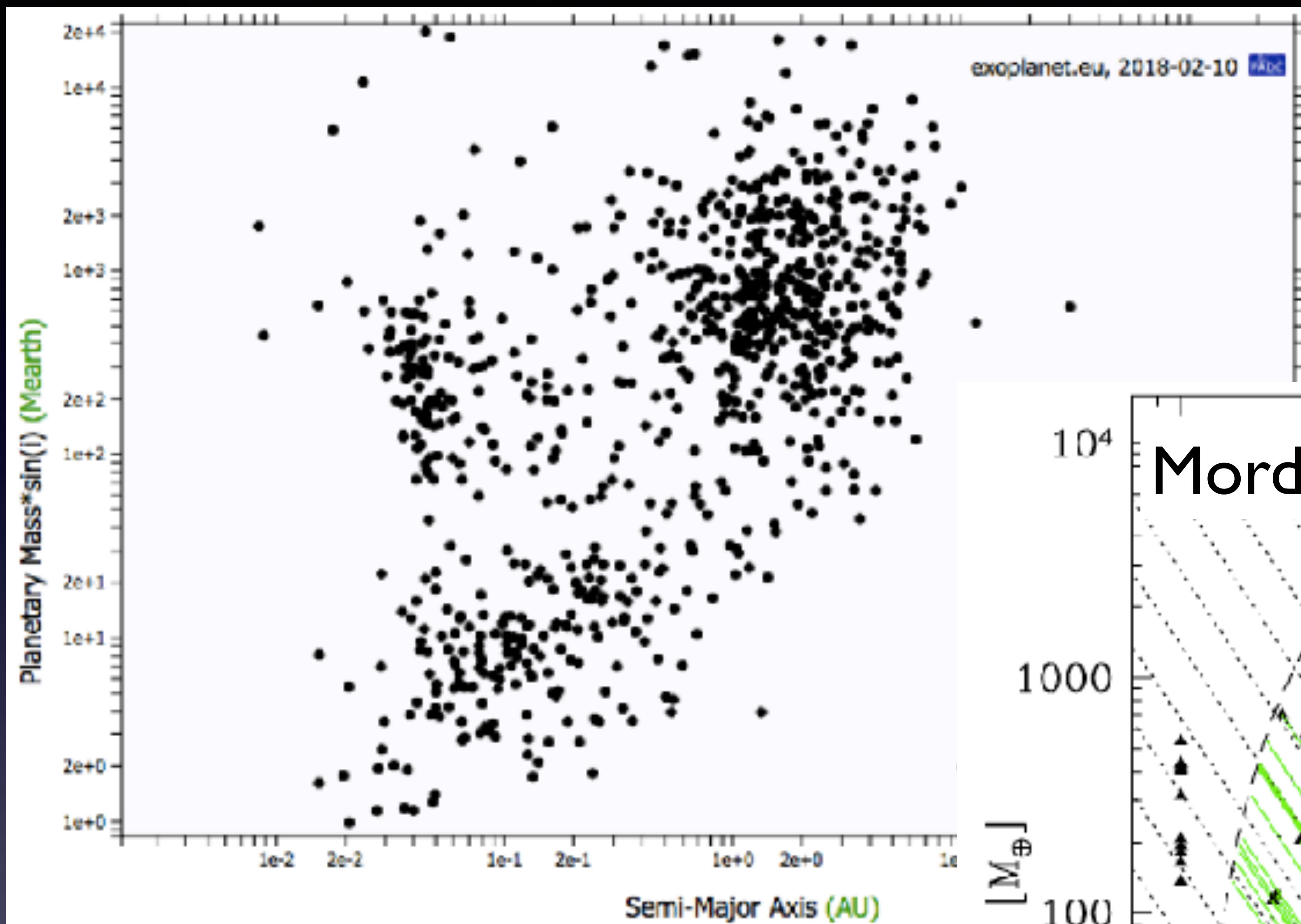
in collaboration with

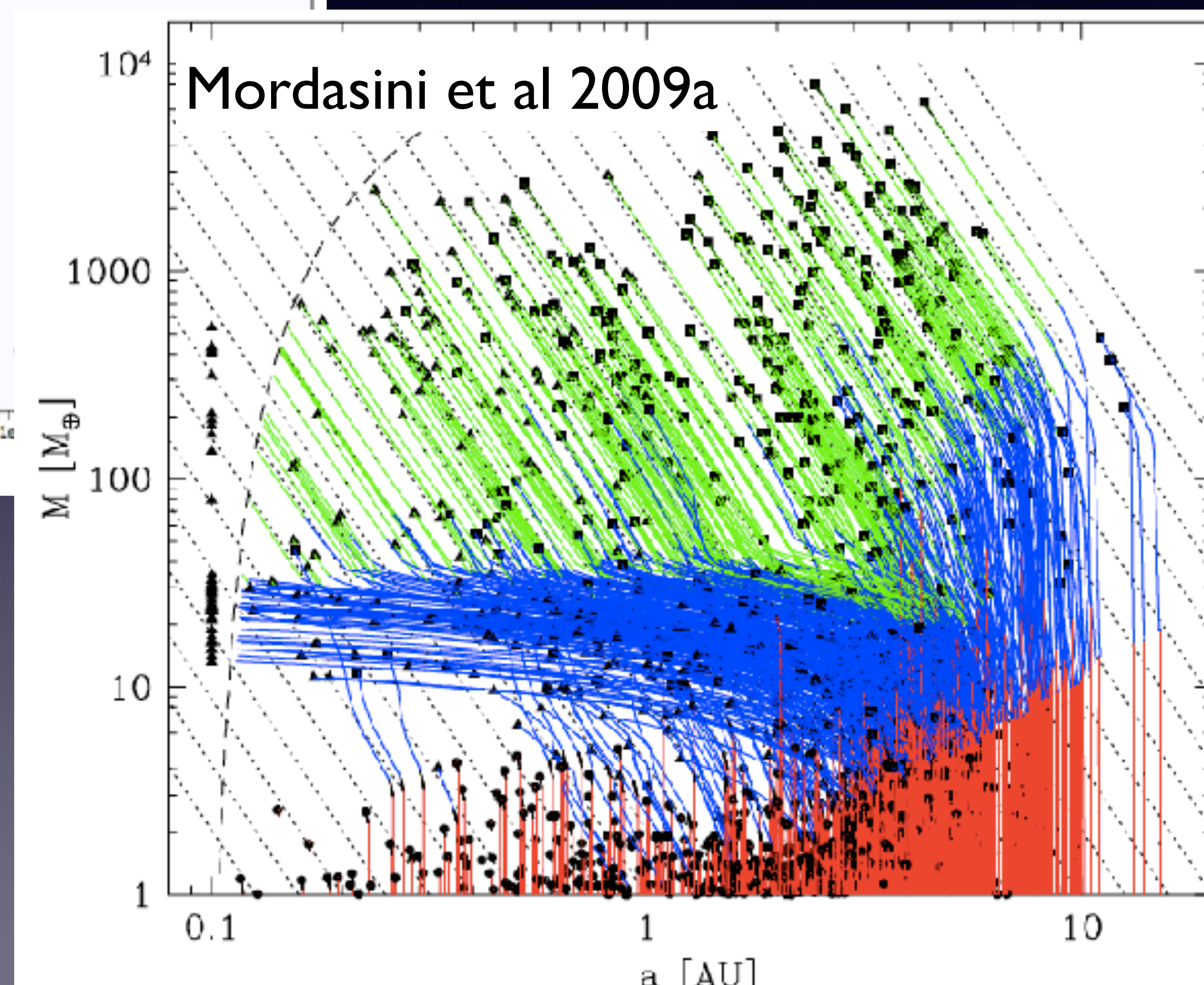
Geoff Bryden, Masahiro Ikoma, Gautam Vasisht, Mark Swain

Exoplanets are Ubiquitous in Our Galaxy



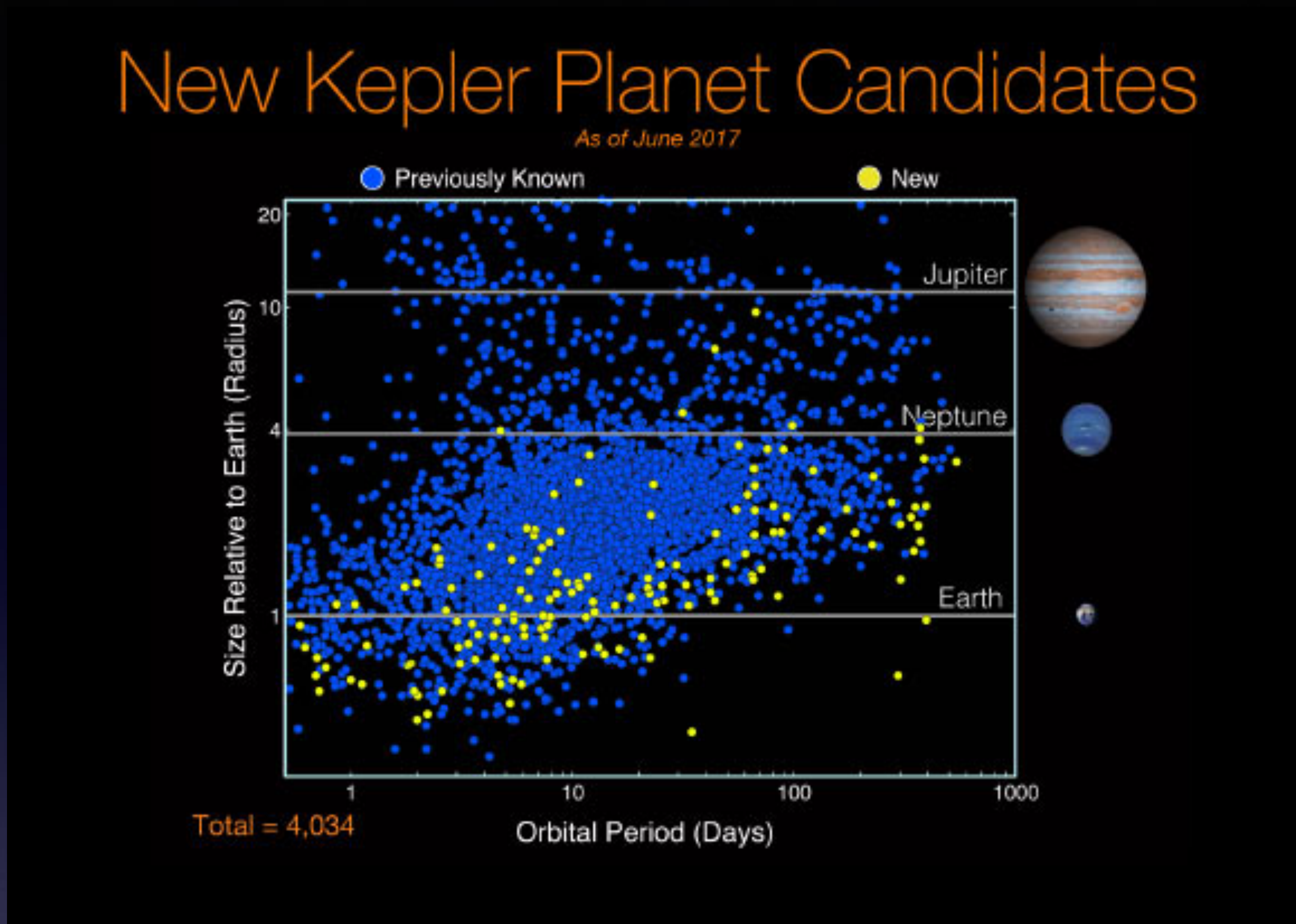
Background 1: How do Planets form?

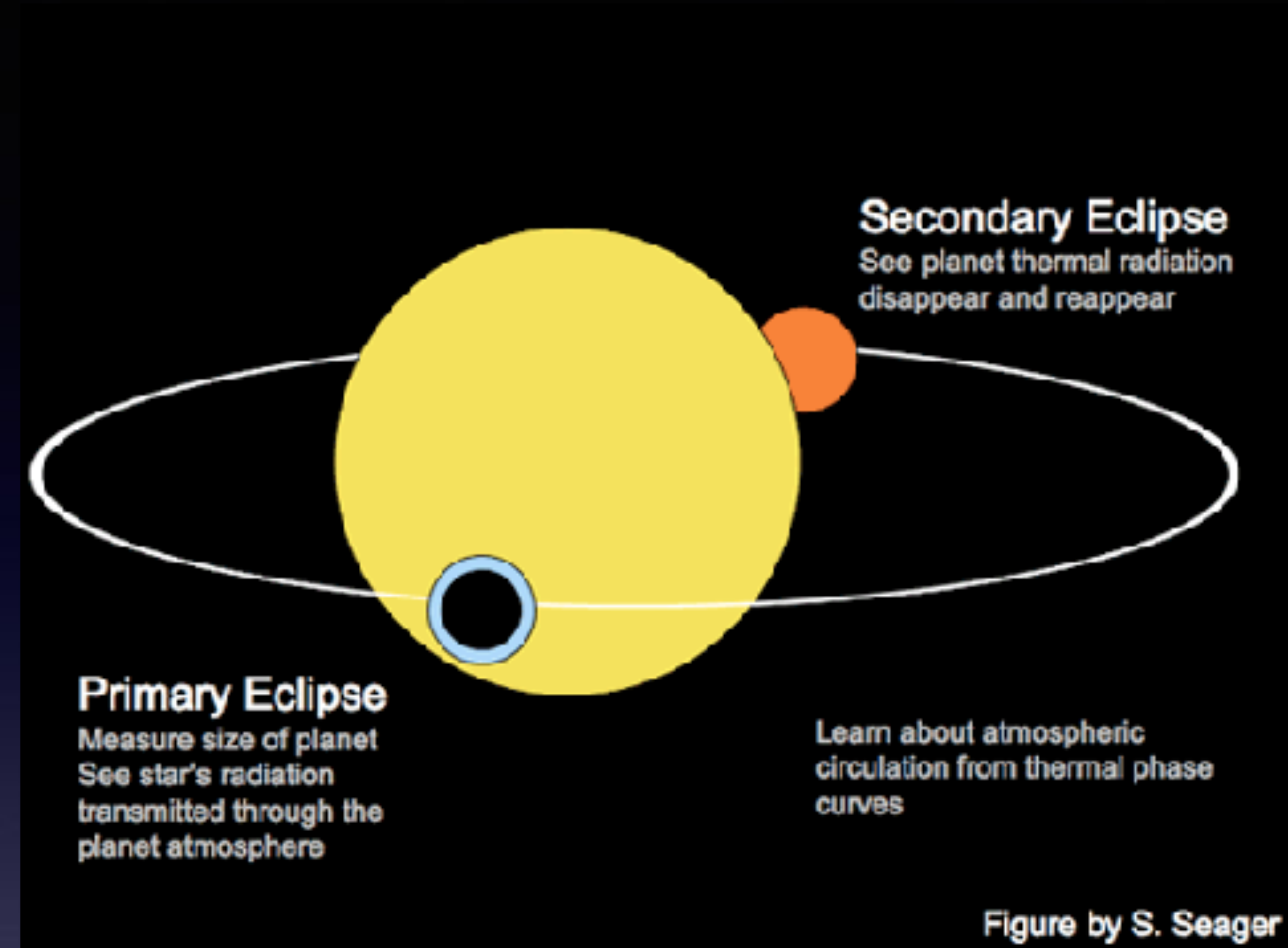




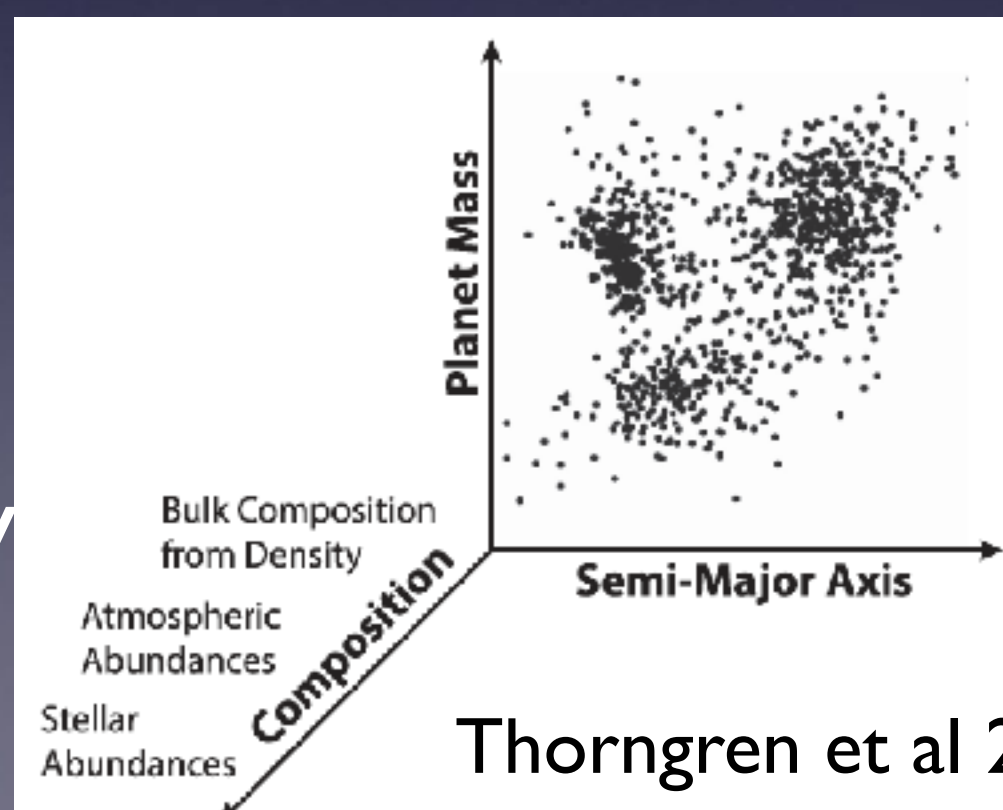
The planet mass-semimajor axis can be observed

Background 2: How do Planets form?





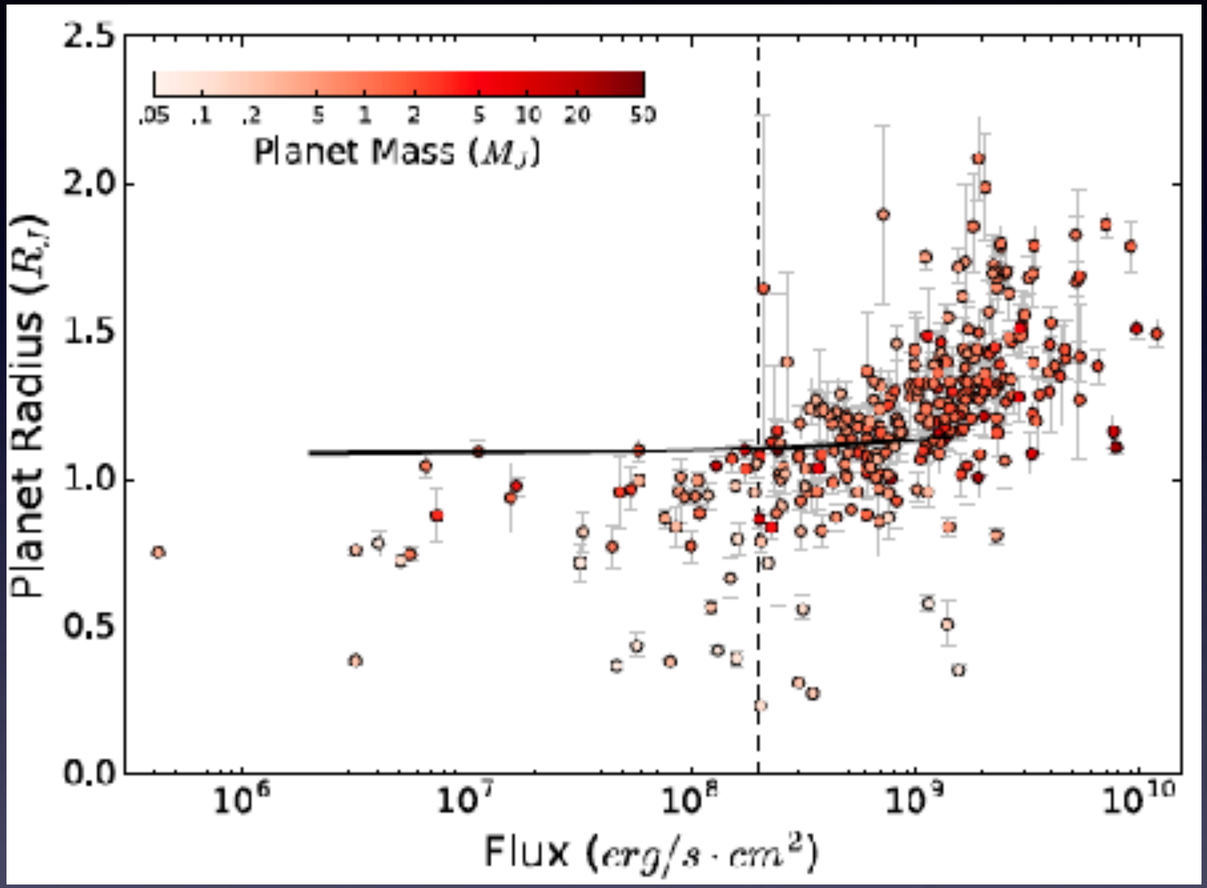
The planet radius can be observed => the bulk density

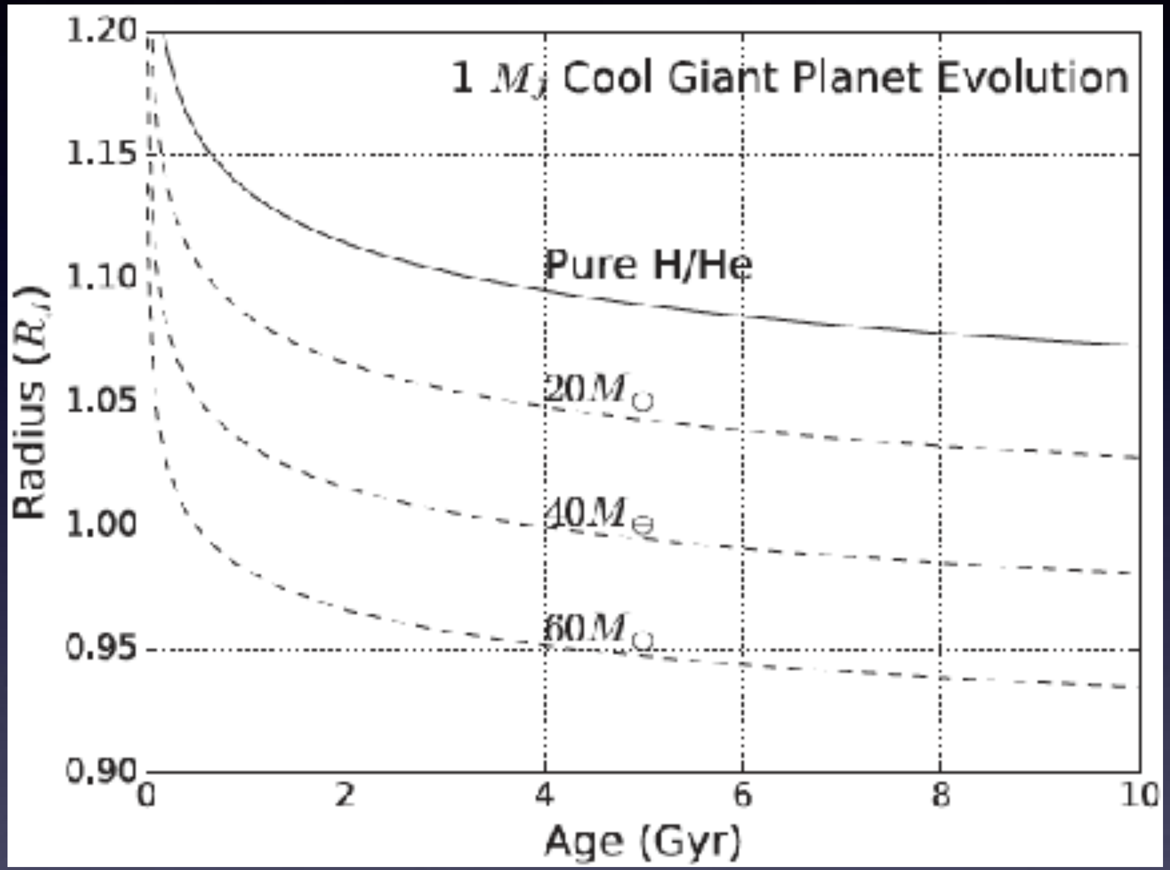


Thorngren et al 2016

The atmosphere can be observed => the composition

Estimate of the heavy element mass in observed exoplanets

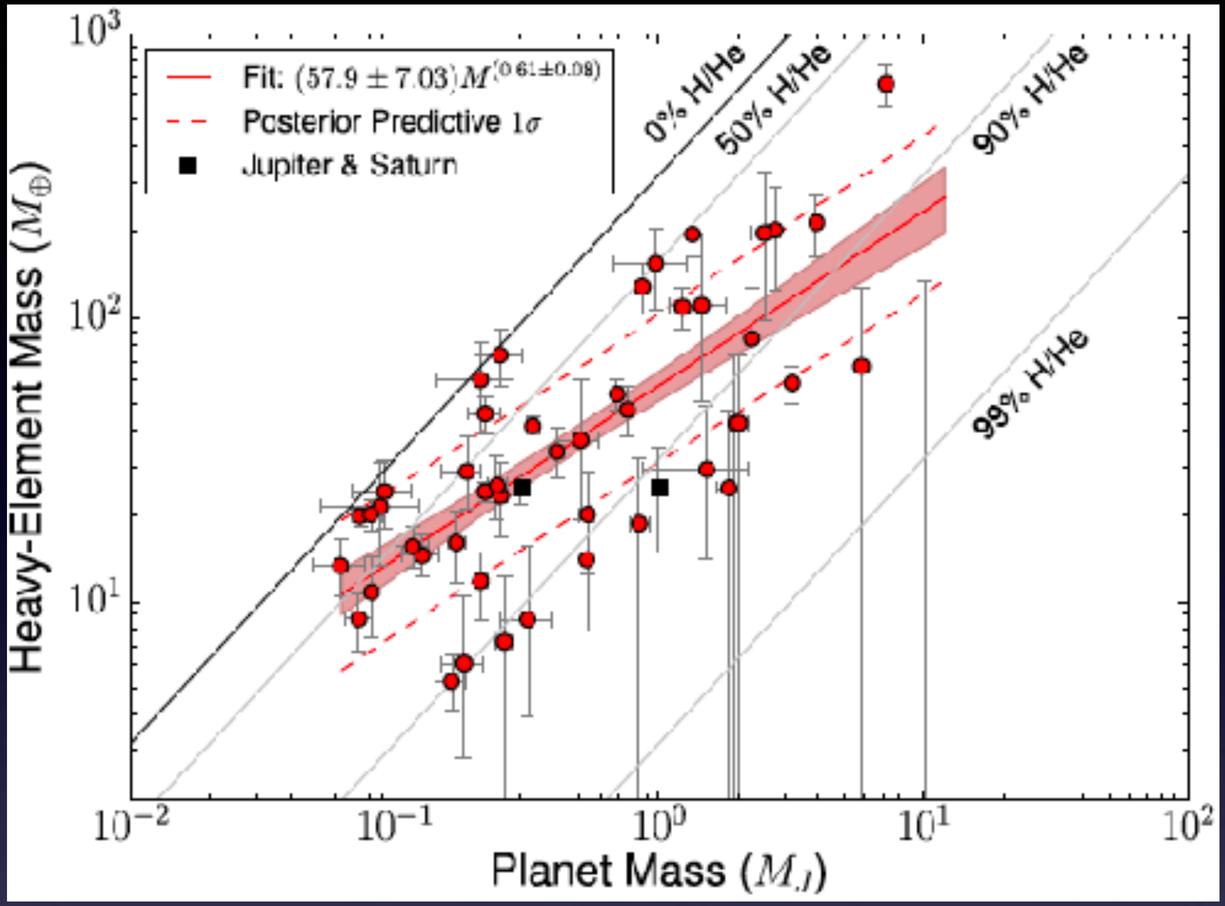


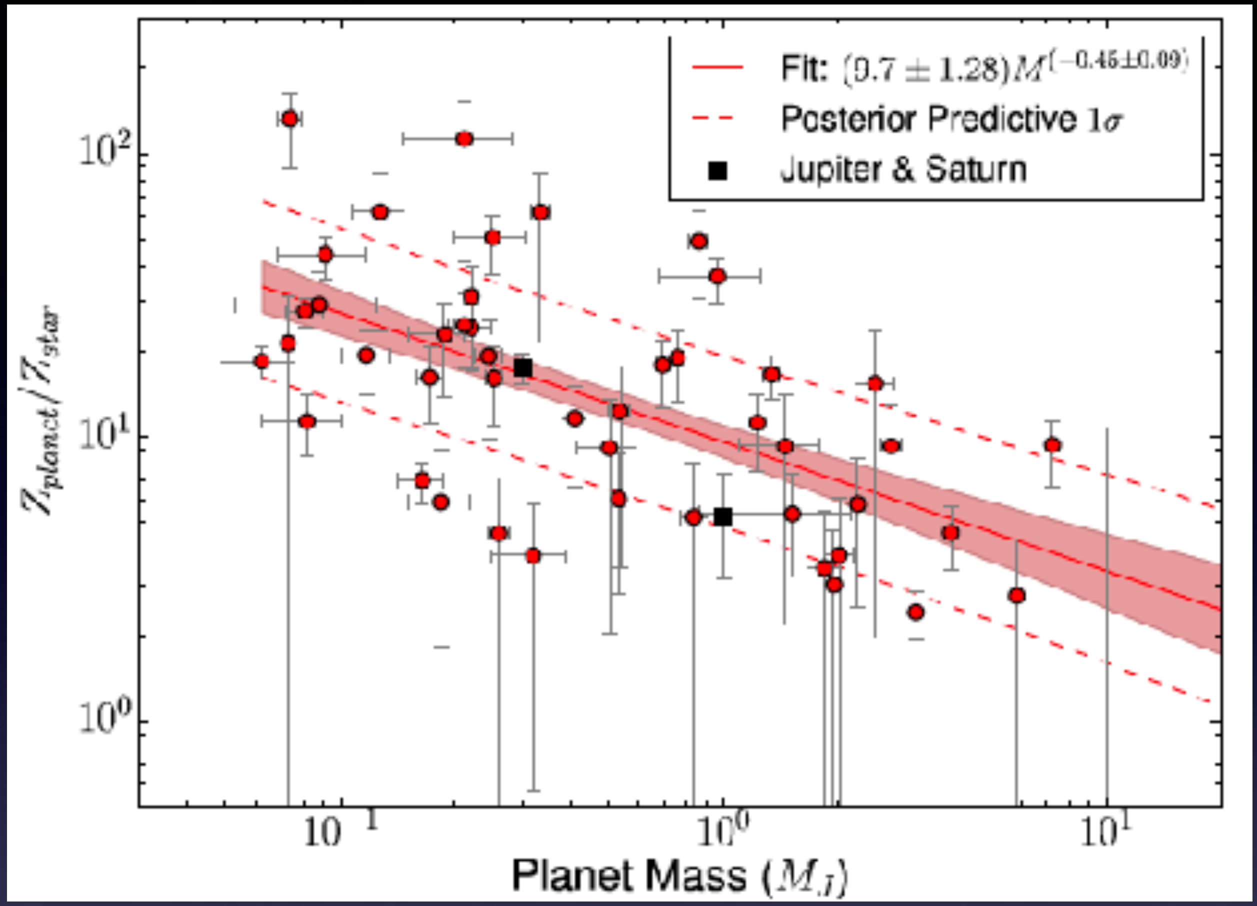


Target selection: relatively cool close-in exoplanets

Compute the radius evolution of planets,
by distribute heavy elements in cores and atmospheres

Results of Thorngren et al 2016





$$M_Z \propto M_p^{\gamma} \text{ with } \gamma = 0.61 \approx 3/5$$

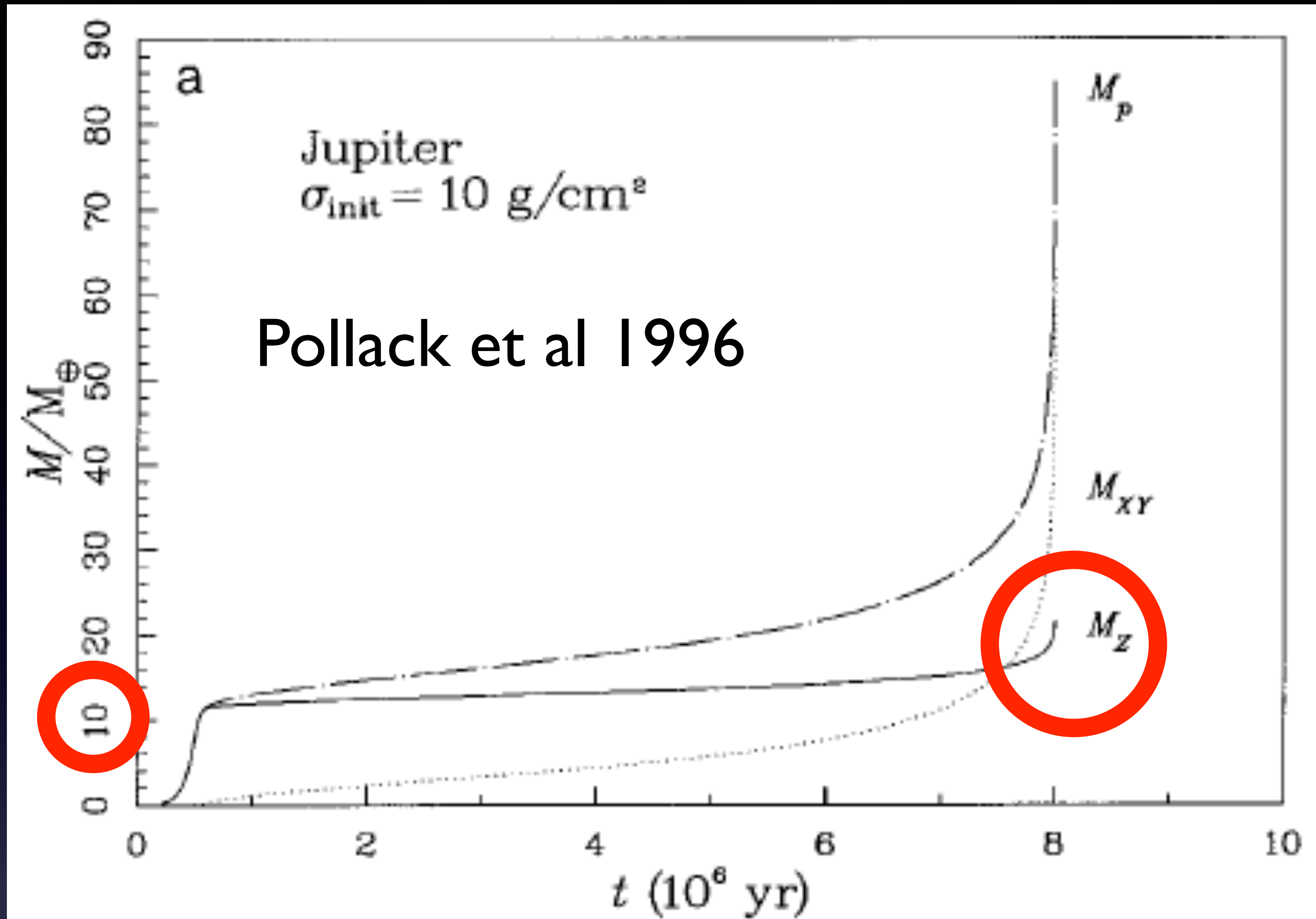
$$\frac{Z_p}{Z_s} = \frac{M_Z}{M_p}\frac{1}{Z_s} \propto M_p^{\alpha} \text{ with } \alpha = -0.45 \approx -2/5$$

$\alpha \approx \gamma - 1$ => M_Z and M_p are almost independent of Z_s

M_Z : the total heavy element mass in planets with the mass of M_p

Z_s : the metallicity of the host star

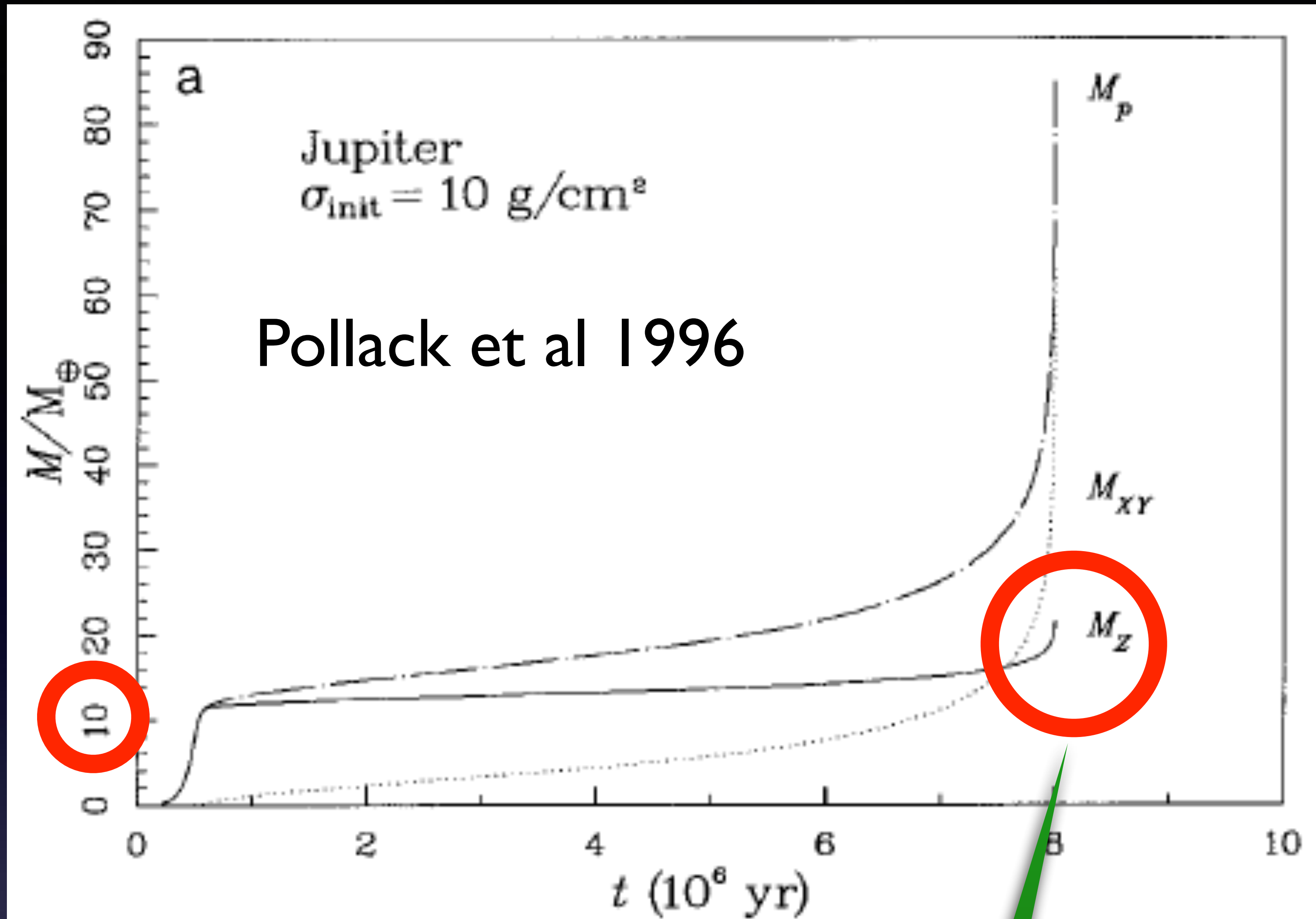
Planet Formation via Core Accretion: Accretion of Gas and Solids



$M_{core} \simeq 10 M_\oplus$

M_Z increases at the final formation stage

Planet Formation via Core Accretion: Accretion of Gas and Solids



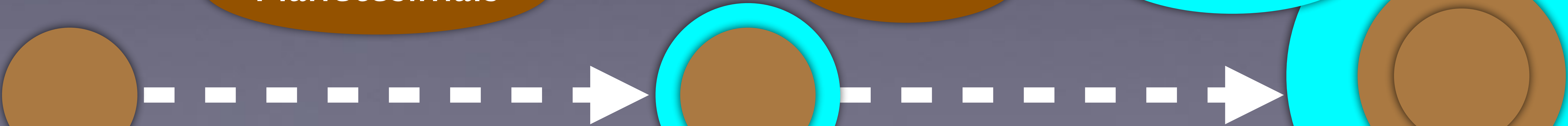
$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

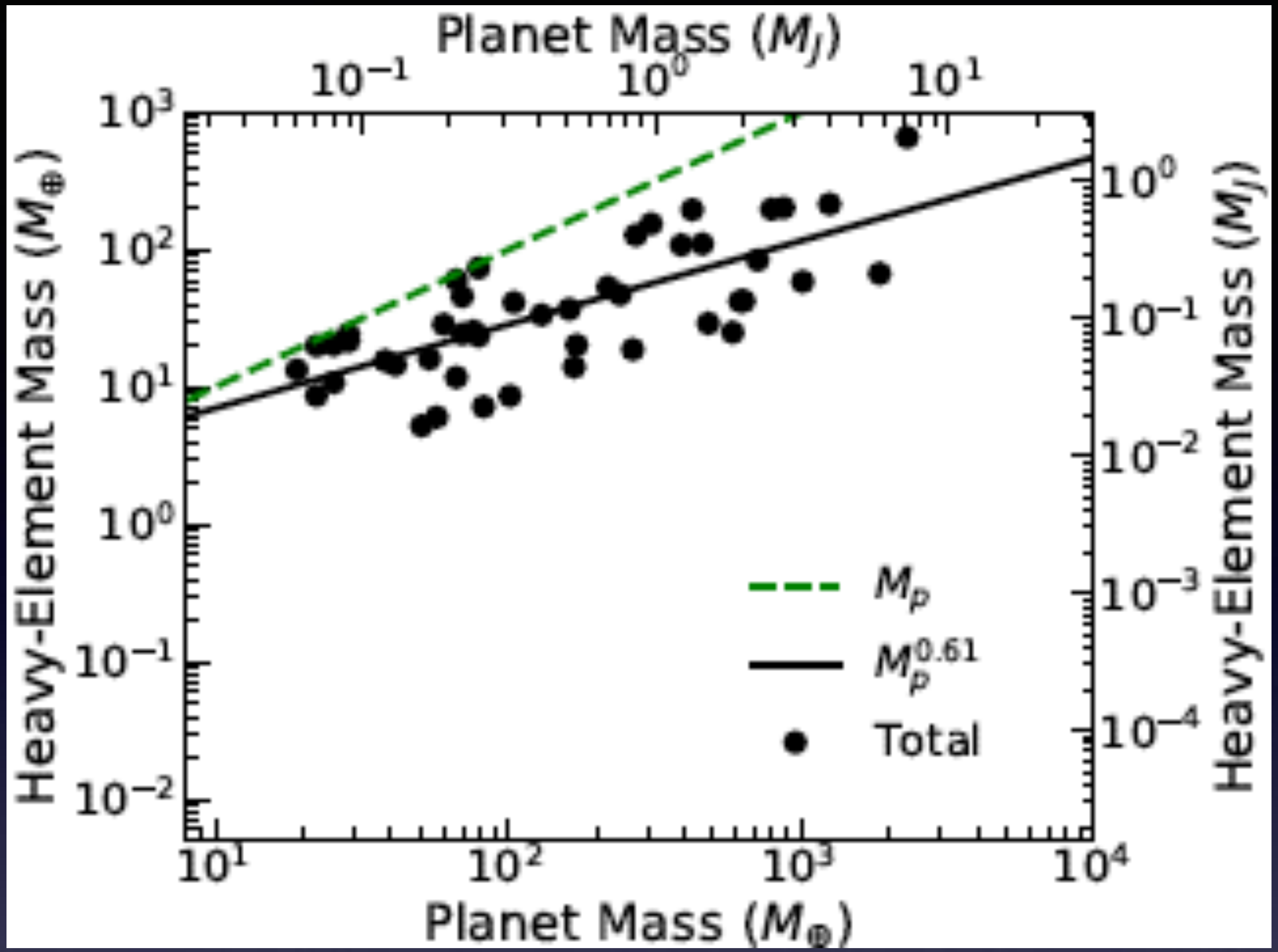
Planetesimals

Pebbles

dust in gas



$$M_{Z,gas} = Z_s M_{XY}$$



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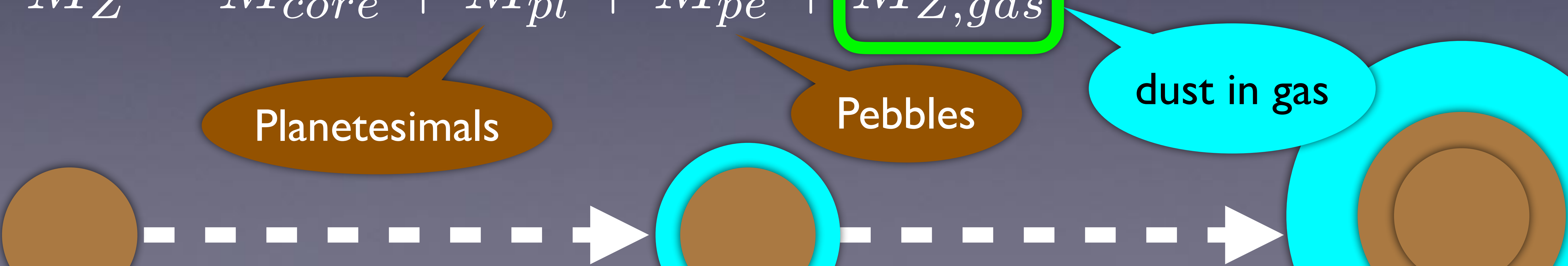

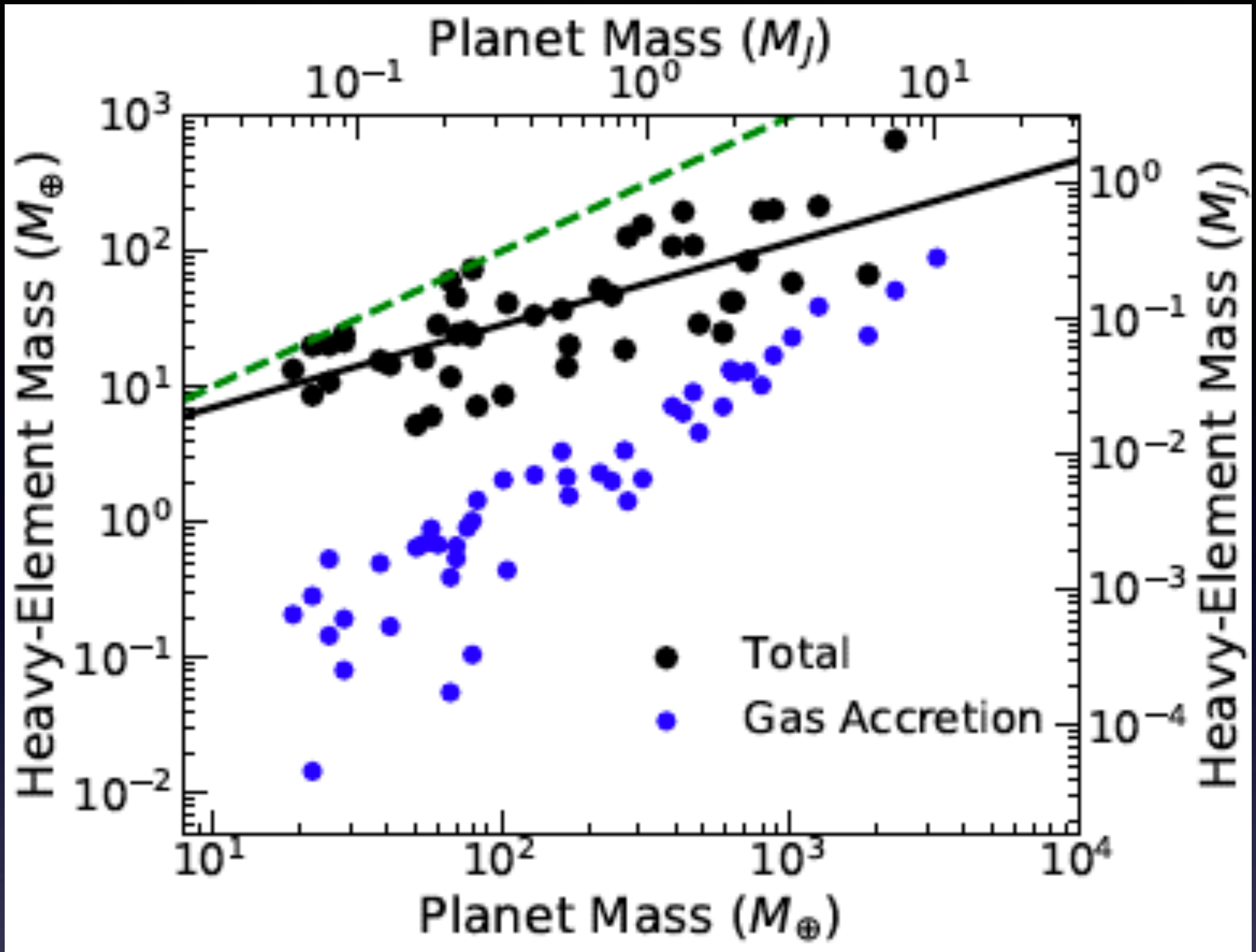

$$M_{Z,gas} = Z_s M_{XY}$$

Contribution arising from gas accretion is negligible

$$M_p = M_{XY} + M_Z$$

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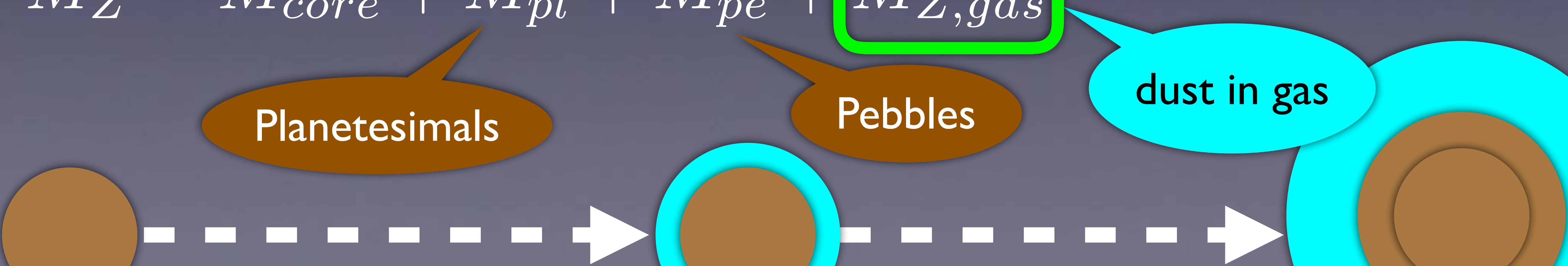

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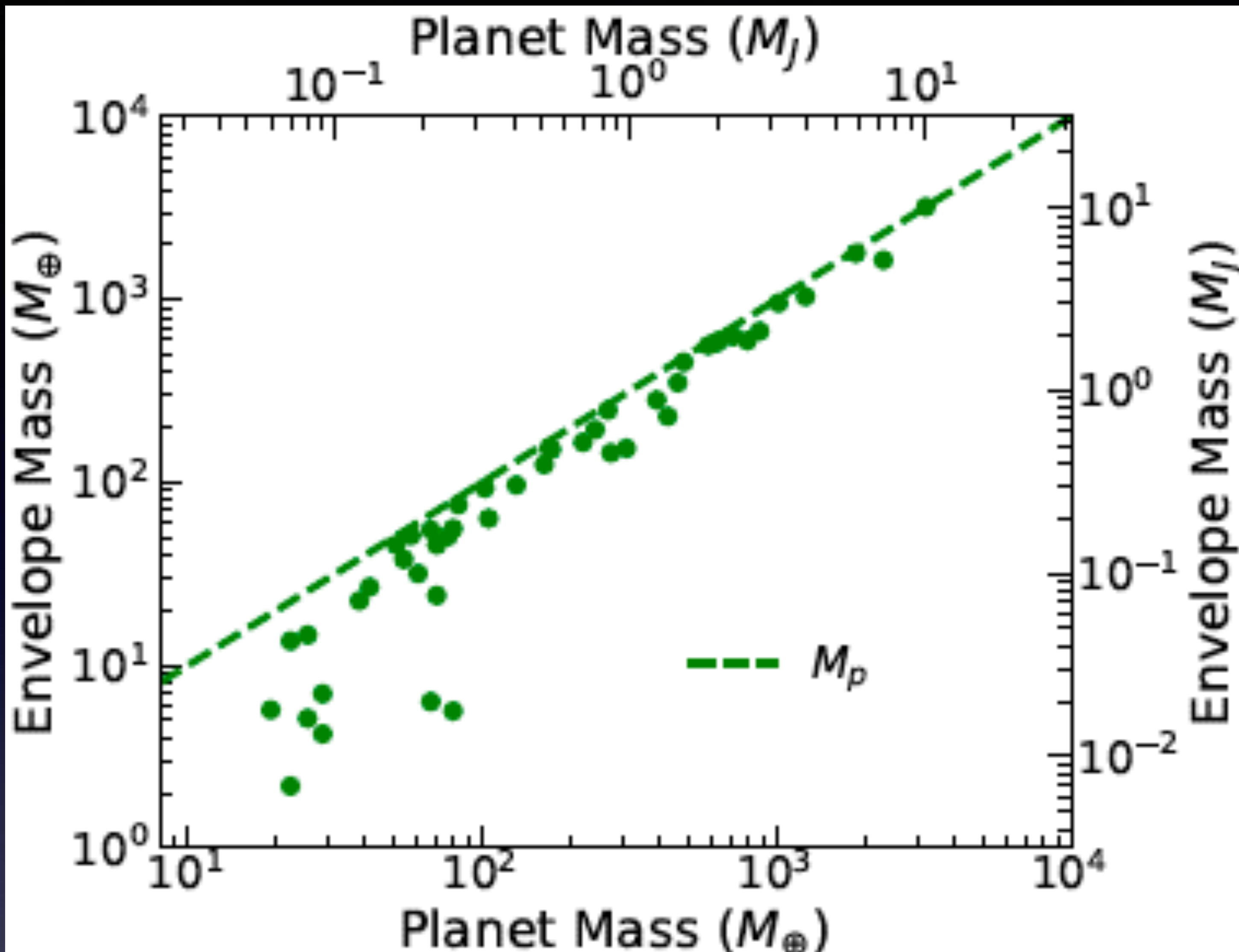

Contribution arising from gas accretion is negligible

Runaway gas accretion occurred for planets with $M_p > 100 M_\oplus$

Some mechanisms are needed for postponing runaway gas accretion

$$M_p = \boxed{M_{XY}} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + \cancel{M_{Z,gas}}$$

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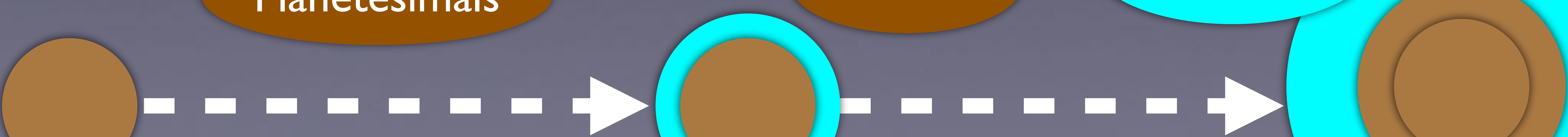
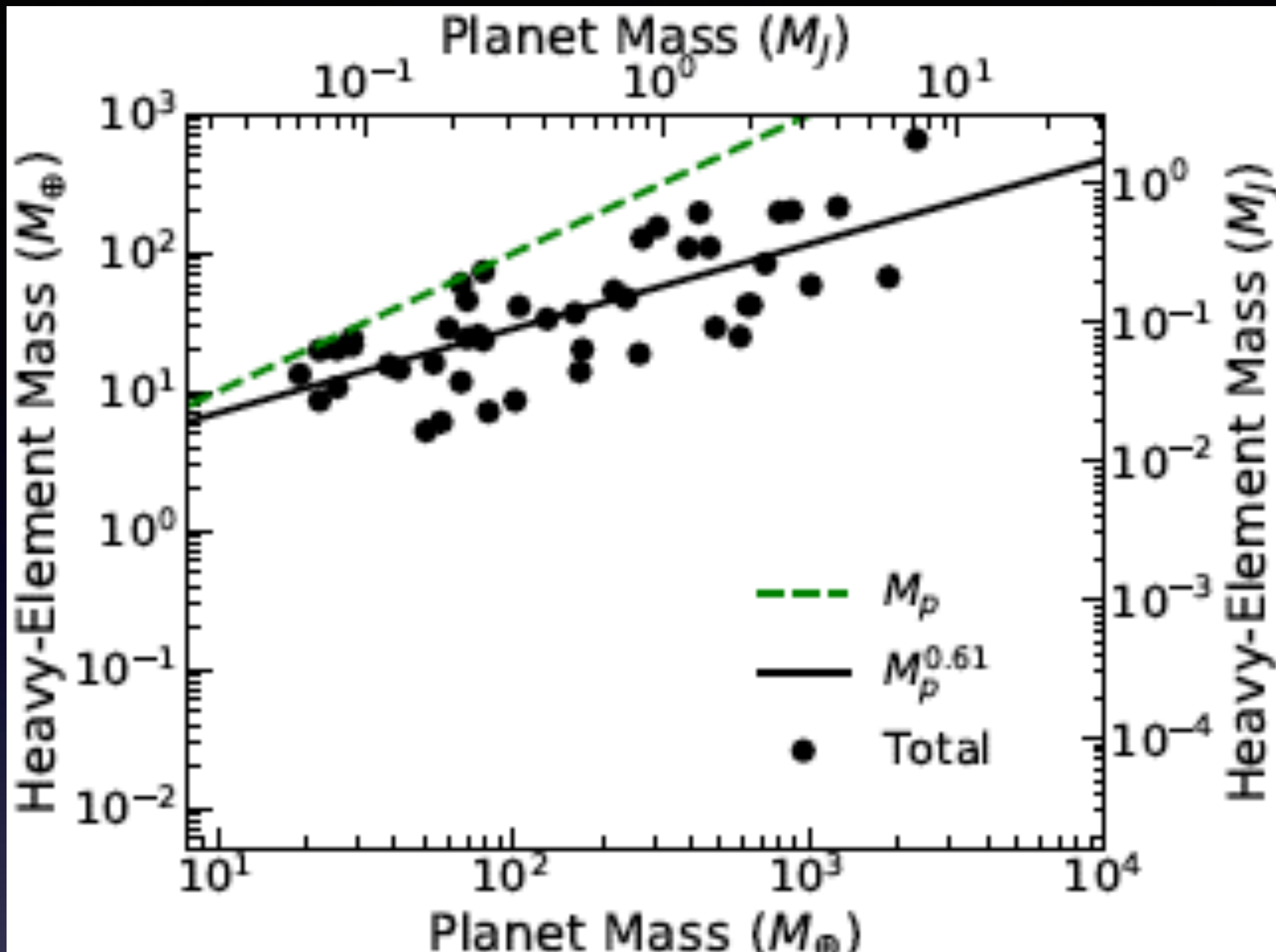
dust in gas





M_{core} is determined by disk parameters for both planetesimal & pebble accretion

$$M_p = M_{XY} + M_Z$$

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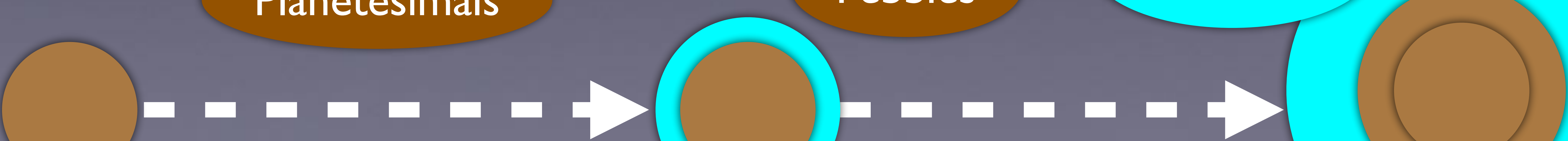

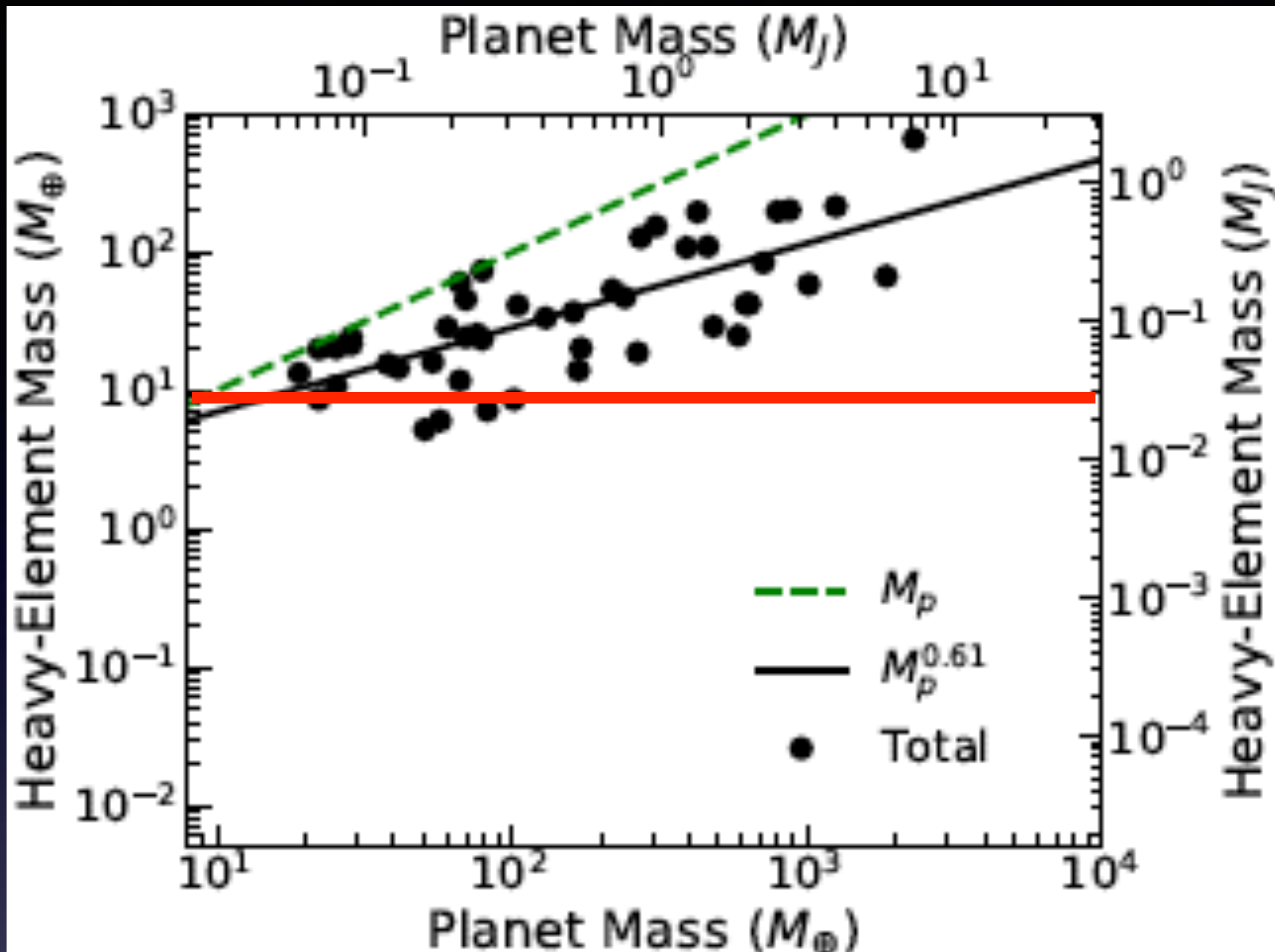

M_{core} is determined by disk parameters for both planetesimal & pebble accretion

M_{core} is independent of M_p for both scenarios

$$M_p = M_{XY} + M_Z$$

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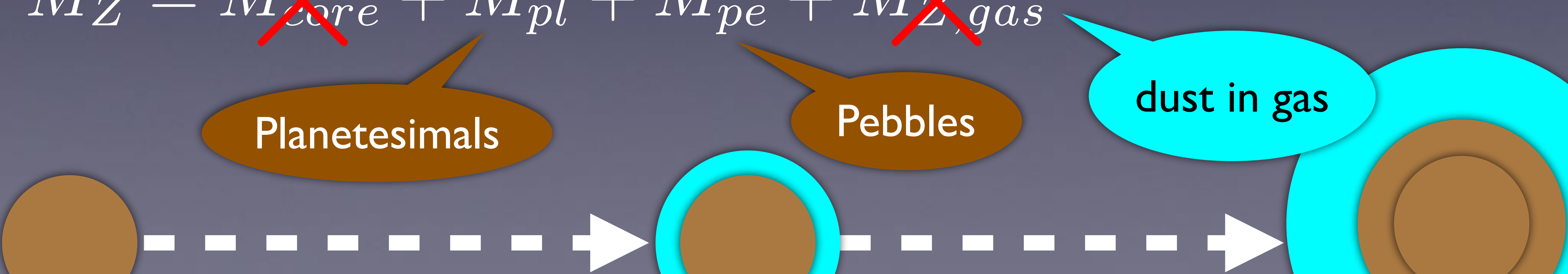

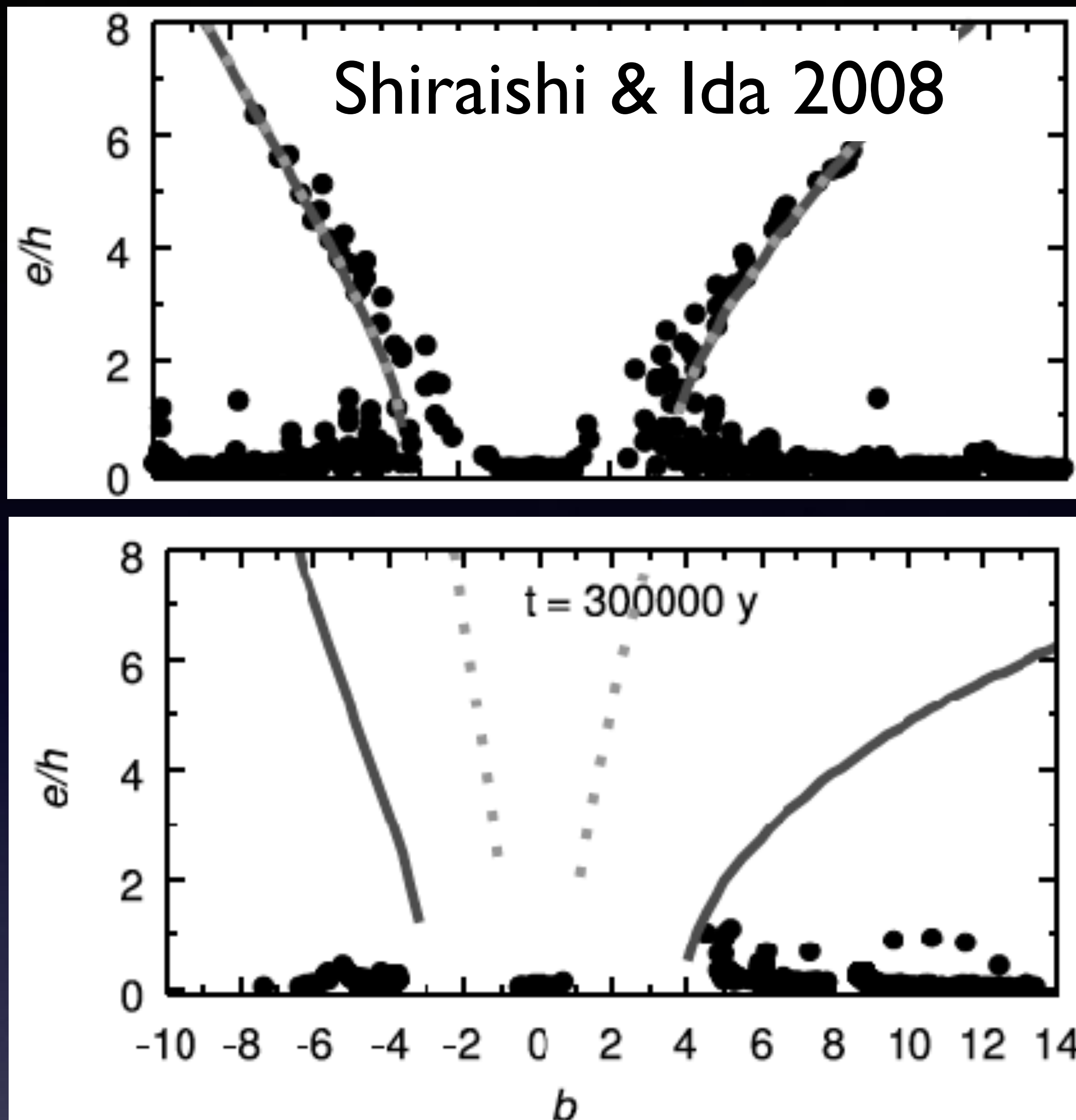

The spatial distribution of planetesimals is the key, which is determined by the gravitational interaction with a protoplanet

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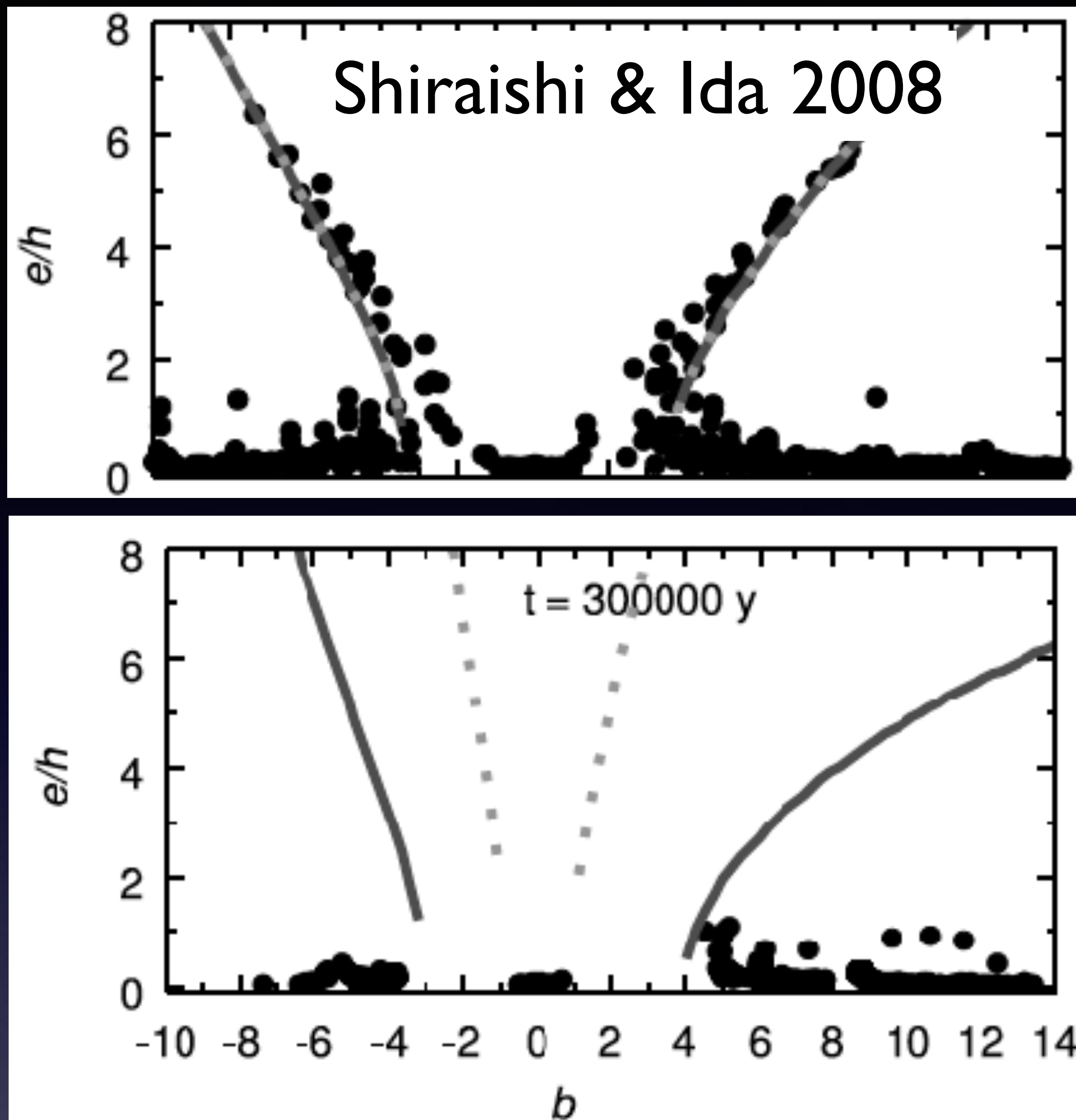

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$M_Z \simeq M_{pl} \propto M_p^{1/3}$ with no gap in planetesimal disks

$M_Z \simeq M_{pl} \propto M_p^{3/5}$ with gaps in planetesimal disks

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Pebbles

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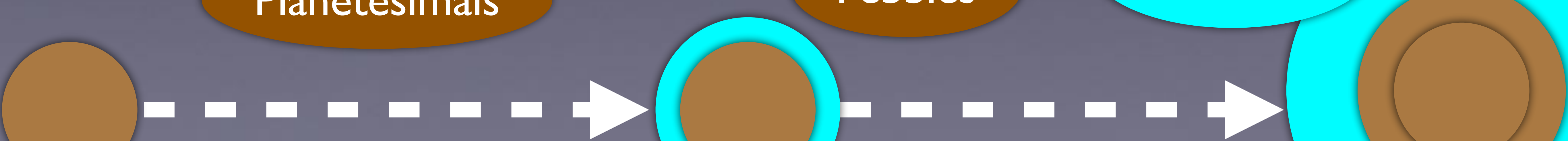

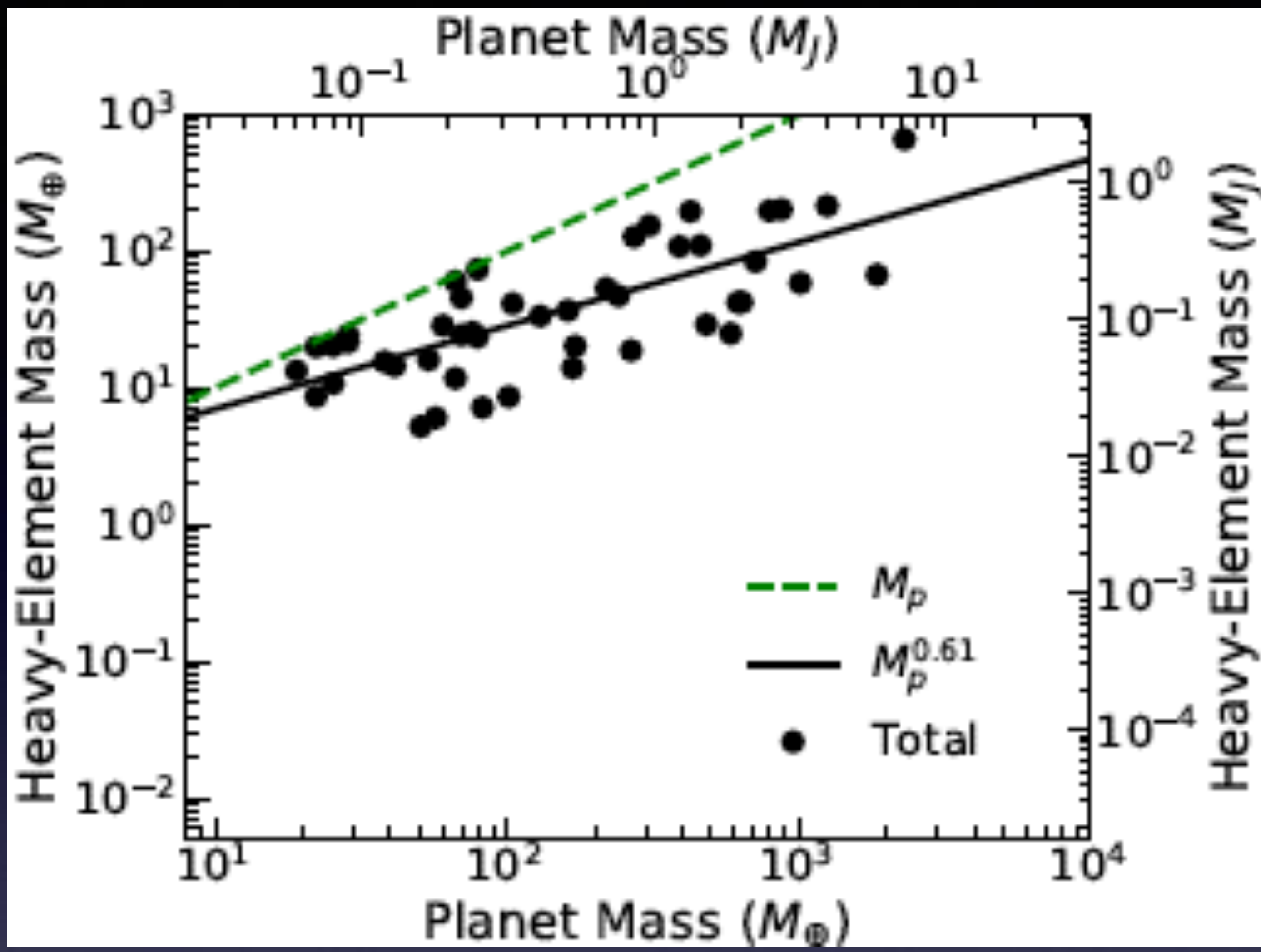

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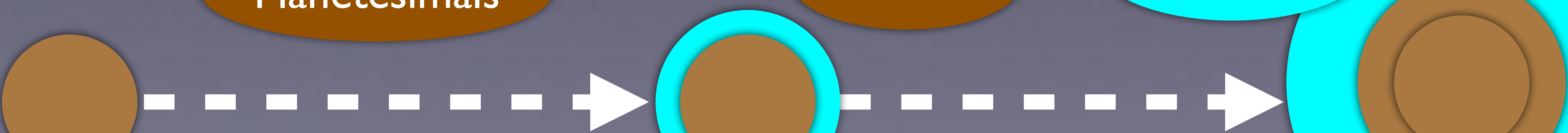

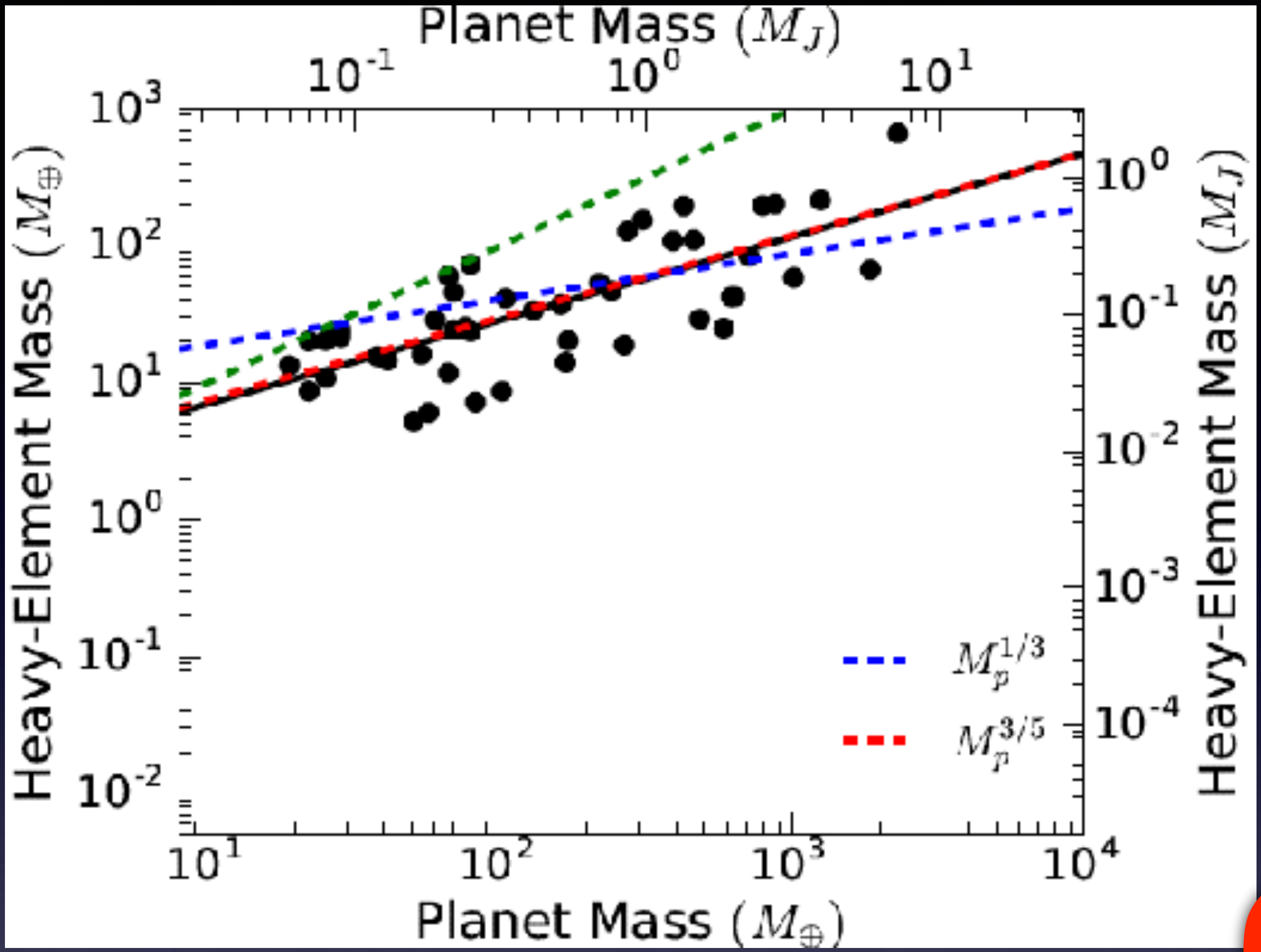

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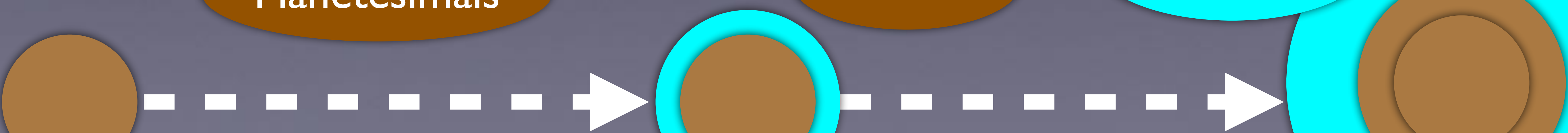

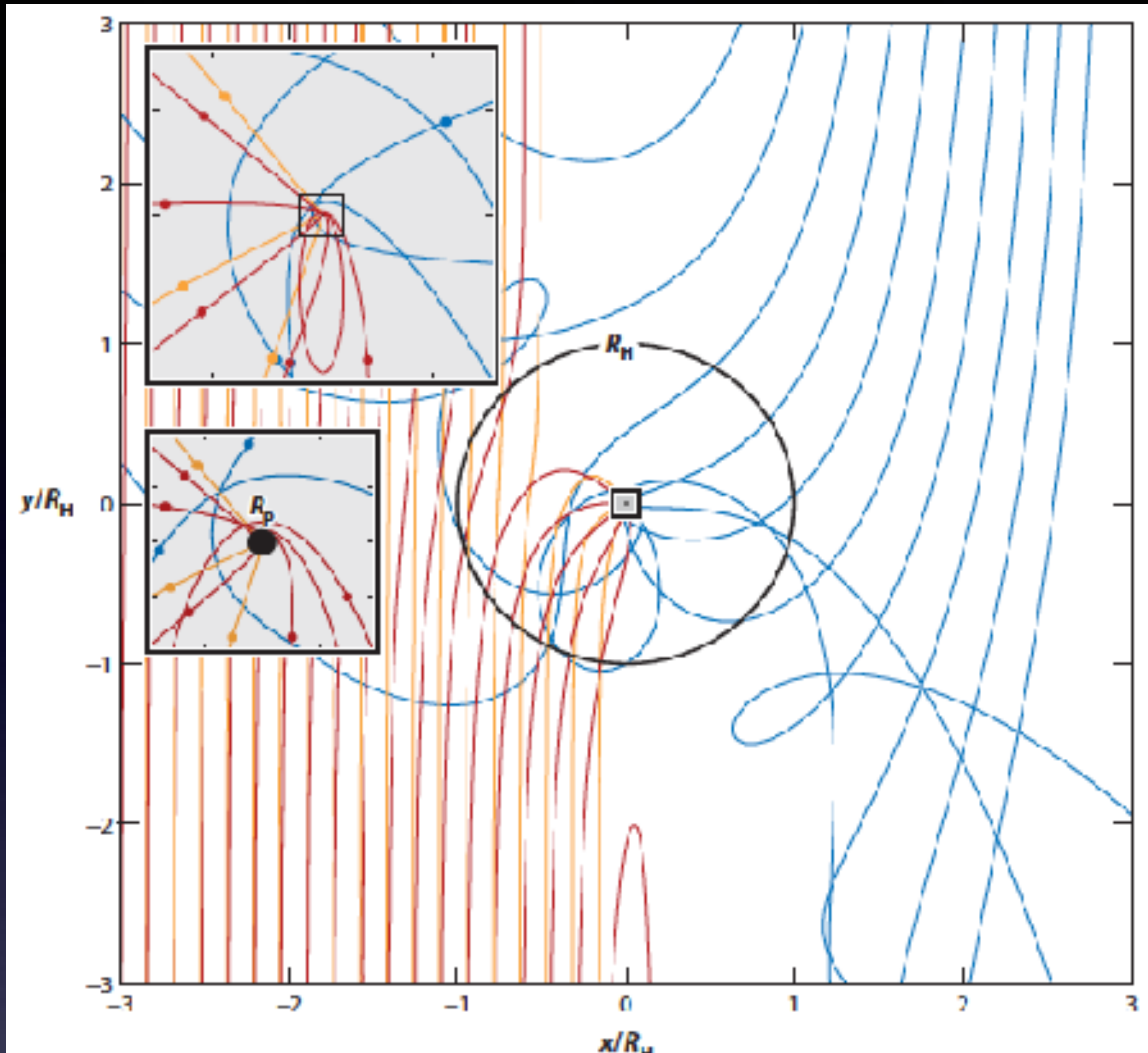

Understanding of pebble accretion is premature

e.g., Johansen & Lambrechts 2017

$$M_p = M_{XY} + M_Z$$

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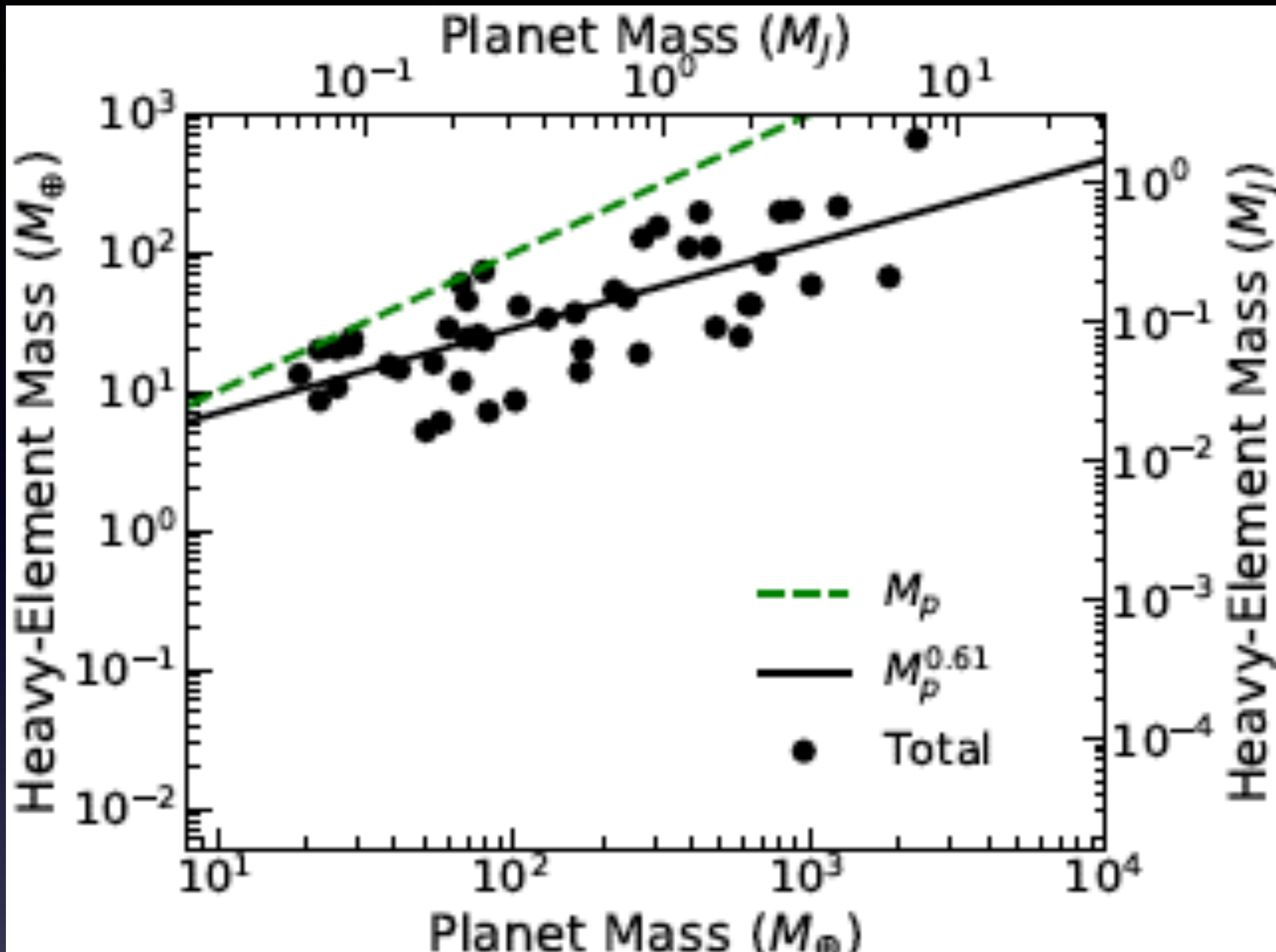

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$$M_Z \simeq M_{pe} \propto M_p^{1/3}$$

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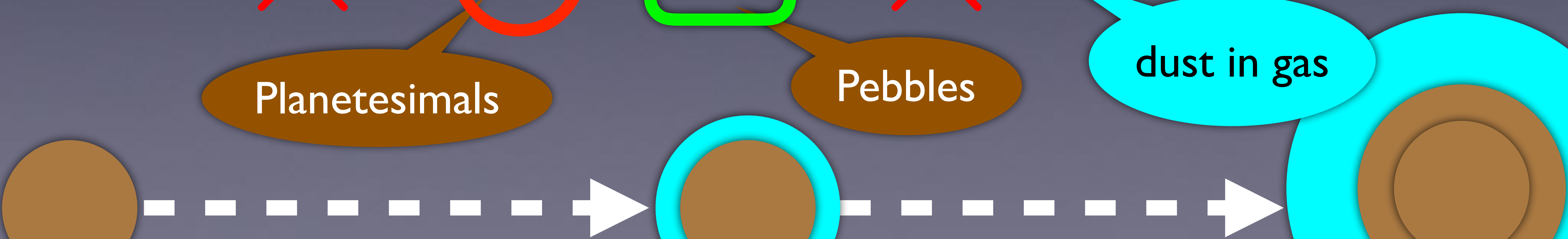

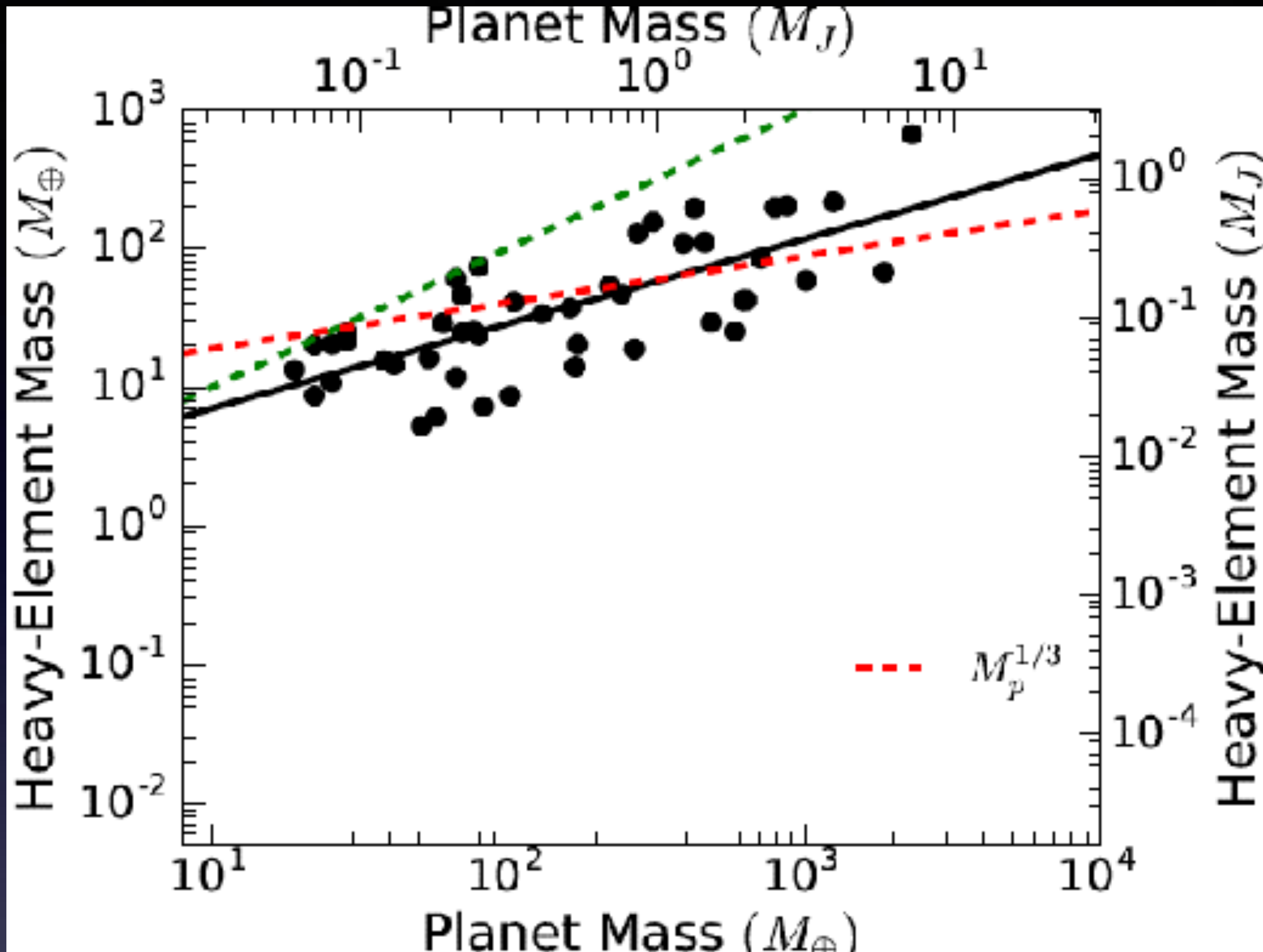

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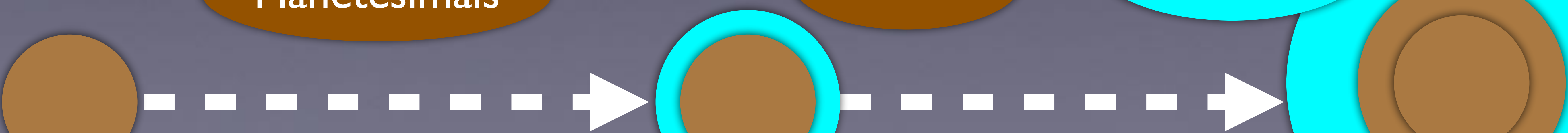

The total heavy elements are determined by the final stage of planet formation

At the stage, solids are accreted onto planets from gapped planetesimal disks

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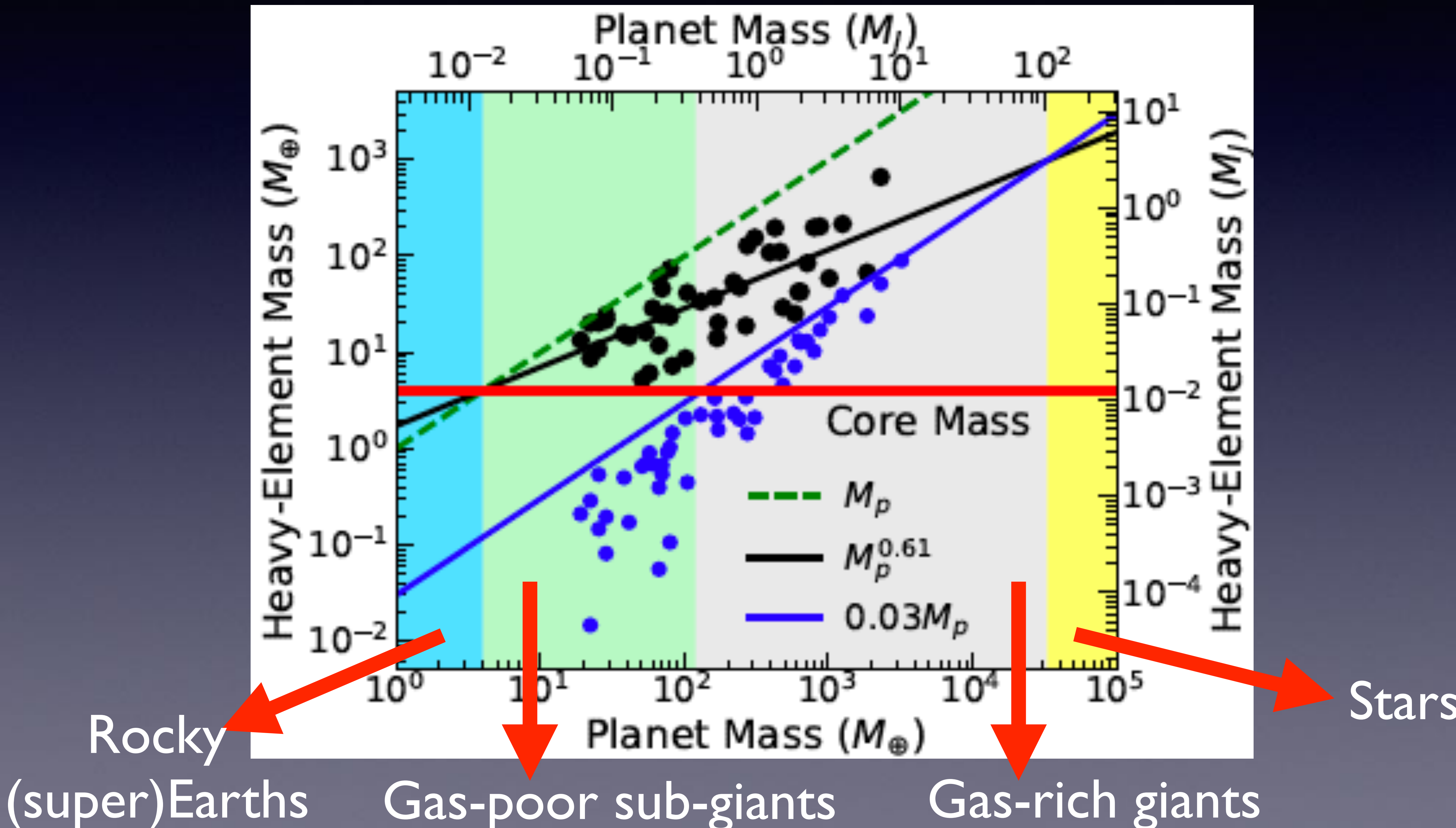
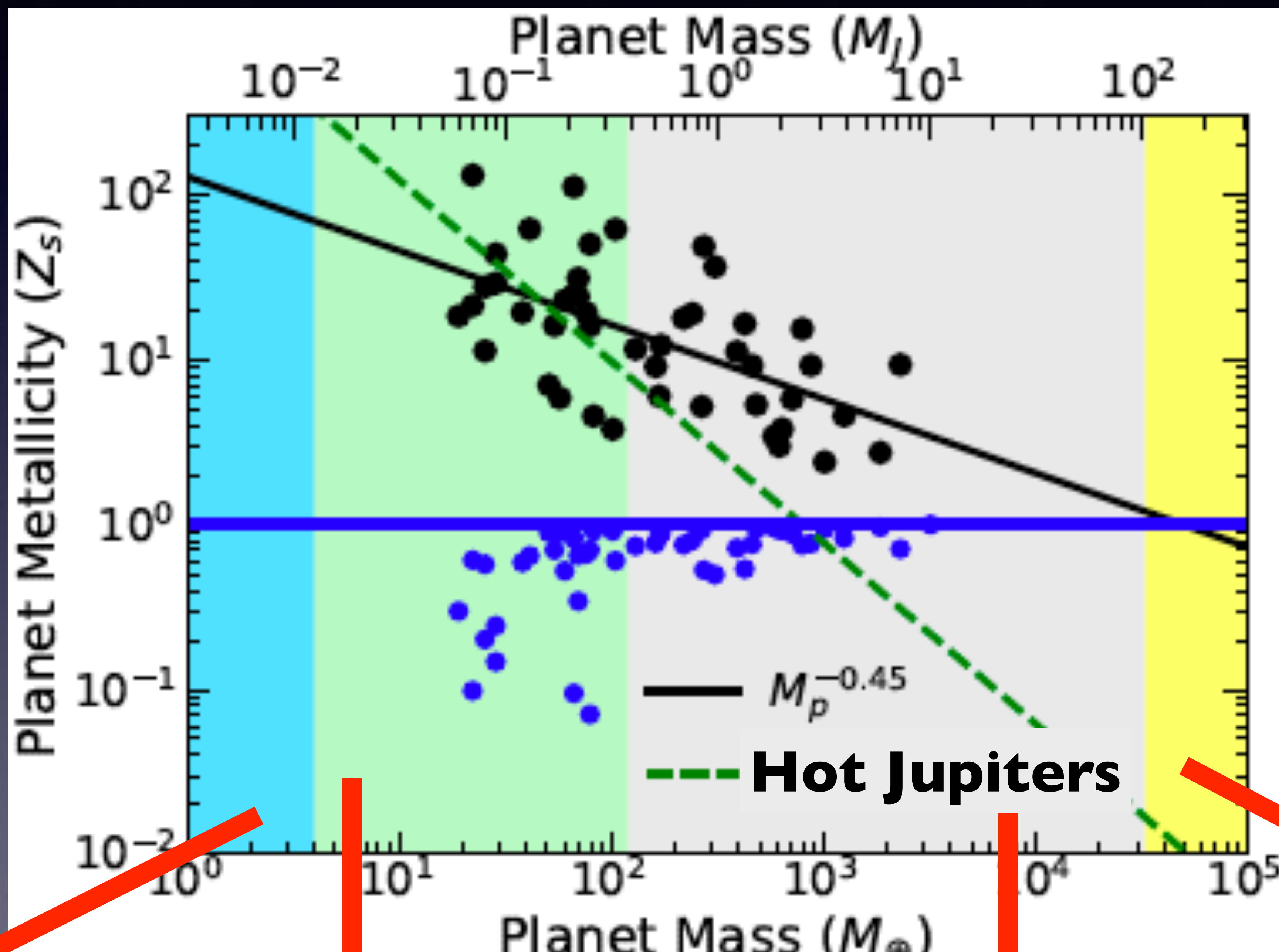


Evolution of atmospheric metallicity can be explored, comparing hot and warm Jupiters

Planetary cores might be fully dissolved into their atmospheres for gas-poor sub-giants



Rocky (super)Earths

Gas-poor sub-giants

Gas-rich giants

Stars

Summary

Hasegawa et al. 2018, submitted

- Formation mechanisms of observed exoplanets are better constrained, by taking into account planet mass, orbital period, and planet composition

- Observed warm Jupiters tend to have correlations:

$$M_Z \propto M_p^{3/5} \qquad \frac{Z_p}{Z_s} = \frac{M_Z}{M_p}\frac{1}{Z_s} \propto M_p^{-2/5}$$

- Our results indicate that the contribution (dust) arising from gas accretion is negligible

- Runaway gas accretion is postponed until $M_p > 100 M_\oplus$

- Accretion of solids from gapped planetesimal disks can reproduce the above trends better

- We propose a classification of observed exoplanets